Age-related Changes in Interlimb Coordination

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This thesis contains no material that has been accepted for a degree or diploma by the University or any other institution. To the best of my knowledge and belief this thesis contains no material previously published or written by another person except where due acknowledgement is made in the text of the thesis.

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Abstract

Age-related changes in motor performance have often been associated with functional decline with advancing age such as general motor slowing, degraded attentional capacity, and declined physiological inhibitory control. The overarching aim of the current series of empirical studies was to investigate the contribution of these functional alterations to age-related changes in motor function.

The first part of the study investigated age-related changes in inter-limb coordination and the associated attentional cost using a dual-task paradigm. The primary task involved the coordination of arm and leg movements performed by limbs on the same (ipsilateral) or opposite (contralateral) sides of the body. Difficulty of the primary task was manipulated by varying movement direction (isodirectional vs non-isodirectional) and movement frequency, with attentional cost being reflected in responses to a secondary probe reaction time task. The results showed that the performance of older adults selectively deteriorated depending on task difficulty. That is, the age-difference was pronounced in the most attentionally demanding condition in which the movement frequency was highest and the motor task was performed simultaneously with a reaction time task.

The second part of the study used electroencephalography (EEG) to provide a direct measure of the CNS activity associated with mental resource allocation in older adults during the performance of the interlimb coordination task. Attentional resource allocation was assessed by Event-Related Potentials (ERPs) during concurrent performance of interlimb coordination tasks and a visual oddball task. The amplitude of the P3b component of the ERP has been associated with the allocation of attentional resources. For both young and older adults coordination performance was less stable and visual reaction times (RTs) were longer during the coordination of ipsilateral limbs than contralateral limbs. Although older adults showed slower RTs to targets in the visual odd ball task, they exhibited similar patterns in P3b latency and amplitude to younger adults. Of particular interest was higher a P3b amplitude at the frontal sites in older adults, suggesting an increased cognitive monitoring of performance with aging.

In the last part of the research the modulation of cortical activity during interlimb coordination was examined using transcranial magnetic stimulation (TMS). The length of the silent period (SP) following a motor evoked potential (MEP) was used as a measure of corticospinal inhibition during the interlimb coordination task. As expected, older adults showed less stable coordination performance than younger adults during production of non-

isodirectional patterns. SP duration was lengthened, indicating increased inhibition, in the young group during the performance of the ipsilateral non-isodirectional pattern. In contrast, the older group showed a consistent level of cortical inhibition across conditions. These results suggest that deterioration in motor performance with advancing age might be associated with the declined ability to modulate inhibitory function.

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Chapter 1 Introduction: Overview

The Australian government predicted that by 2051 the proportion of the population older than 65yrs will double (26-28% of Australia's population) in comparison to that of 2004 and half the population in Australia will be older than 50yrs (Australian Bureau of Statistics, 2006). The projected future health care cost is estimated at an extra 17.07 billion in today's dollars to provide similar quality and level of health services (Department of Health and Aged Care, 1999). Facing these predictions, it is reasonable to aim to keep individuals independent and healthy for as long as possible. Precious resources for the health system will be conserved by keeping the individual healthy and independent, reducing avoidable accidents, and minimizing the need for hospitalization or residential care.

This research aims to contribute to a fundamental understanding of changes to the human motor control system that occur with age. For older adults the quality of life is greatly affected by their ability to carry out daily tasks, social activities, and recreational pursuits with independence, effectiveness, and vigour (Greene & Williams, 1996). Physical impairments with aging often induce physically, socially, and psychologically negative outcomes, including dependence on others, social isolation, depression, and injuries

(Cummings & Nevitt, 1989; Katz, 1983; Rowe & Kahn, 1987). Above all, declines in motor and cognitive ability are the most ubiquitous signs of the aging process (Birren, Woods, & Williams, 1980). Attenuated motor coordination can also be an early sign of cognitive impairment (Camicioli, Howieson, Oken, Sexton, & Kaye, 1998), and declined speed on a manual task has been shown to predict loss of functional independence in daily living skills better than medical examination (Williams, Gaylord, & McGahie, 1990). Thus, delaying the decline of physical capability, especially motor coordination ability may contribute to maintaining quality of life.

In the field of gerontology a large body of research has reported that proficiency of motor function declines with advancing age (Christou & Carlton, 2001; Contreras-Vidal, Teulings, & Stelmach, 1998; Inglin & Woollacott, 1988; Ketcham & Stelmach, 2001; Melzer, Benjuya, & Kaplanski, 2001; Spirduso, 1995; Stelmach, 1989; Woollacott, Shumway-Cook, & Nashner, 1986), though, some motor functions appear to remain relatively intact (e.g., Lee, Wishart, & Murdoch, 2002; Warabi, Noda, & Kato, 1986; Williams & Bird, 1992; Wishart, Lee, Murdoch, & Hodges, 2000). The three main hypotheses that have been put forward to explain age-related decline of movement control are summarized in the following subsections.

Explanations for Age-Related Changes in Movement Control

General slowing hypothesis

The first hypothesis reflects the traditional view of aging that there is an overall slowing in cognitive, motor, neural, and perceptual processes (e.g., Hunter, Thompson, & Roger, 2001; Morgan et al., 1994; Salthouse, 1991, 1996). It has been argued that degraded performance in older adults is due to less efficient and slower processing in underlying processes, which may lead to the adoption of a strategy by older adults to slow down their movements. In any kind of motor task, if speed is prioritized, the accuracy degrades, and vice versa. Therefore it is necessary to constantly balance speed and accuracy for optimal performance. For older adults, because they tend to be more "error averse" (Goggin & Stelmach, 1990), they prefer to be slow and accurate rather than moving fast and inaccurate. The strategy not to hurry may be adopted because older individuals are aware that their processes become less efficient and slower with age. Thus, it is possible that the slowing strategy is a response to real declines in cognitive function or neural deficits (Hedden & Gabrieli, 2004).

Another explanation of general slowing is the notion of increased "noise" in neural networks of motor and perceptual systems (Li & Sikstrom, 2002). Noise refers to the

random neural fluctuations (i.e., neural noise) that interfere with the transmission of information within the CNS which leads to declined performance (Sosnoff & Newell, 2006). The neural noise occurs in afferent pathways and in the brain (Welford, 1988). It has been argued, for example, that because of the increasing noise in motor and perceptual systems, older adults tend to make slow movements in order to achieve successful performance (Walker, Philbin, & Spruell, 1996). Inherent noise in the motor system disturbs correct execution of motor output (Fitts, 1954) and the greater the amount of force involved in the movement the greater the motor noise (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). The problem is that as the ratio of noise per force level increases with age, older adults experience greater noise when executing a motor task than younger individuals who perform the same task with a similar amount of force. That is, older adults need to produce slower movements compared to young adults in order to maintain similar levels of accuracy of movement as young adults. In addition to the noise in the motor system, older adults tend to have more noise than young adults in the perceptual system, particularly the visual processing system (Cremer & Zeef, 1987; Verrillo & Verrillo, 1985), which contributes to the slowing down of movement in older adults since visual feedback plays crucial role for most movements (Walker et al., 1996). Therefore older adults are required

to choose between making a rapid movement with greater error or an accurate movement at a slow speed. Similar to the neural noise hypothesis, the loss of complexity hypothesis provides an useful perspective on age-related behavioral changes (Goldberger et al., 2002; Newell, Vaillancourt, & Sosnoff, 2006). In order to perform cognitive or motor tasks, physiological functions are required to integrate the complex networks of neural control systems, feedback loops, and other regulatory mechanisms (Lipsitz, 2004). The loss of complexity hypothesis argues that aging and/or disease are associated with a loss of complexity in the dynamics of integrated physiological processes leading to a declined adaptive capacity in older adults (Lipstiz, 2004). The function of the hypothesized increasing noise and loss of complexity with advancing age is somewhat debatable. Recent neuroimaging studies have observed "overactivation" in the aging brain (e.g., Heuninckx et al., 2004, 2008; see Ward, 2006 for review, details of the overactivation in the aging brain will be outlined in the section 4.1) which can be a generalized nonfunctional spread of activity attributable to either increased neural noise or loss of neural specialization (loss of complexity) (Langenecker & Nielson, 2003; Nielson et al., 2002). Alternatively overactivation has been linked to compensatory mechanisms for various neural/behavioral deficits (e.g., neurodegeneration, attentional problems, reduction in sensory function, etc.)

(Cabeza, 2002; Cabeza, Anderson, Locantore, & McIntosh, 2002; Grady, 2002; Madden, Turkington et al., 1999; Reuter-Lorenz et al., 2000; Reuter-Lorenz & Lustig, 2005). In general, overacativation in aging brain has not been consistently associated with either the noise or loss of complexity hypotheses.

Resource allocation hypothesis

The second major hypothesis has focused on cognitive deficits as the underlying mechanism of age-related deficits in motor performance (Heuninckx, Debaere, Wenderoth, Verschueren, & Swinnen, 2004; McDowd & Shaw, 2000). In particular, attention is regarded as a main mediator in the control of "a resource" or "a limited mental capacity[1]" (Kahneman, 1973). It has been argued that age-related decline in attentional ability is the basis for a variety of age-related behavioural inefficiencies (McDowd & Shaw, 2000). A declined attentional resource in older adults has also been suggested as the basis of changes in skilled motor performance in older adults (e.g., Shumway-Cook & Woollacott, 2000). For example, it has been shown that a relatively automatic motor task such as gait requires

[1] The terms *capacity* and *resources* are used interchangeably in the current research which is a common practice in the area, e.g., McDowd & Shaw, 2000.

more attentional cost for older adults in comparison to young adults (Sparrow, Begg, & Parker, 2006; Woollacott & Shumway-Cook, 2002).

In addition to the above mentioned hypothesis of a decrease in the amount of attentional resources, it has been also argued that the regulation of attentional function declines with advancing age. In order to successfully perform a motor task, it is necessary to regulate motor output and utilize feedback information from the periphery to adjust behaviour in an optimal manner (Lajoie, Teasdale, Bard, & Fleury, 1996). However, it has been argued that processing of feedback information for successful performance becomes less efficient with age since the ability to divide and / or allocate attentional resources effectively declines in older adults (Kramer, Hahn, & Gopher, 1999; Serrien, Swinnen, & Stelmach, 2000). At the same time, increased motor noise (Walker et al., 1996) or degraded sensory feedback with age (Skinner, Barrack, & Cook, 1984; Stelmach & Sirica, 1986) forces older adults to rely more on cognitive control of movements (Albinet, Tomporowski, & Beasman, 2006). Hence, older adults face a predicament in which there is an increasing demand for attentional control of movements to detect degraded sensory information, while attentional processing itself is also becoming inefficient (Lindenberger, Marsiske, & Baltes, 2000).

Inhibition hypothesis

The third major hypothesis argues that age-related decline of inhibitory processes underlies degraded cognitive task (Burke, 1997; Hasher & Zacks, 1988; Kane, Hasher, Stoltzfus, Zacks, & Connelly, 1994; Kramer, Humphrey, Larish, Logan, & Strayer, 1994) and motor performance (Dustman, Emmerson, & Shearer, 1996; Dustman, Shearer, & Emmerson, 1993). In the CNS neurotransmitters excite two functionally distinct neural pathways, excitation and inhibition. Excitation decreases the threshold of the cell membrane and enhances the probability of cell firing, while inhibition increases the threshold of the cell membrane and lowers the probability of cell firing (Creasey & Rapoport, 1985). Human behaviour involves an ongoing balance between excitation and inhibition mechanisms within and among neuronal systems (Dustman et al., 1996). Thus neural mechanisms are used in performance of motor or cognitive tasks involving the processing task-relevant information and producing goal-relevant responses as well as ignoring irrelevant information or responses. However, as older adults generally have reduced inhibitory functions (Nielson, Langenecker, & Garavan, 2002), it is hypothesized that task performance declines due to the lack of sound control of neural output between excitation

and inhibition with advancing age. Consistent with this hypothesis, a number of studies employing the transcranial magnetic stimulation (TMS) technique indicate that the level of cortical inhibition decreases with age (Hortobagyi, del Olmo, & Rothwell, 2006; Kossev, Schrader, Däuper, Dengler, & Rollnik, 2002; Oliviero et al., 2006; Peinemann, Lehner, Conrad, & Siebner, 2001; Prout & Eisen, 1994; Sale & Semmler, 2005). In addition to data suggesting that declined task performance may be due to the degraded inhibitory control with advancing age (Hashtroudi, Johnson, & Chrosniak, 1990; McDowd & Filion, 1995; McDowd, Oseas-Kreger, & Filion, 1995), recent studies using other neurophysiological techniques including Electroencephalography (EEG) (Dustman et al., 1996; Dustman et al., 1993) and functional magnetic resonance imaging (fMRI) (Nielson et al., 2002) have provided evidence of distinct cortical activity patterns in older adults compared to young adults when performing tasks that require inhibitory control. Using fMRI, for example, Nielson et al. (2002) found bilateral activation of the left and right hemispheres in older adults during a button-pressing task requiring response inhibition to non-target stimuli, whereas in young adults the right hemisphere, particularly prefrontal and parietal areas, was predominantly engaged during such tasks (e.g., Casey et al., 1997; Chao & Knight, 1997; Garavan, Ross, & Stein, 1999; Konishi et al., 1999). Dustman and colleagues (Dustman et

al., 1996) suggested that homogeneity of brain activity is a sign of reduced central inhibition with advancing age.

In summary, the above hypotheses have been advanced to explain age-related changes in motor function and there is empirical support for each hypothesis. However, it is still unclear the extent to which each hypothesis contributes to the age-related changes in motor function. It is also possible that the suggested mechanisms underlying performance changes in older adults operate together at different levels of processing.

Rationale and general aims

Of particular interest in the present research are age-related changes in interlimb coordination, which involves the spatiotemporal organization of multiple limbs or segments (Heuninckx et al., 2004). The ability to produce specific patterns of interlimb coordination is an essential aspect of daily activities including walking, driving, playing sports and musical instruments, and manipulating objects. Although a number of studies have examined interlimb coordination in young adults (see review, Swinnen, 2002), relatively few studies have investigated age-related changes in interlimb coordination (e.g., Greene & Williams, 1996; Heuninckx et al., 2004; Heuninckx, Wenderoth, Debaere, Peeters, &

Swinnen, 2005; Heuninckx, Wenderoth, & Swinnen, 2008; Lee et al., 2002; Serrien et al., 2000; Wishart et al., 2000). It is important to investigate the effect of aging on interlimb coordination in relation to the above hypotheses since age-related changes in attentional and inhibitory processes are possibly interacting with the motor functions required to perform interlimb coordination. The declined ability to coordinate multiple limbs will impact on daily living, which eventually decreases the quality of life and functional independence of older adults.

To this end, the current research consisted of three phases that investigated the age-related differences in the ability to coordinate upper- and lower-limbs. Part 1 of the research investigated the role of movement speed and attentional function in the performance of interlimb coordination. Previous research has indicated the importance of controlling for general motor slowing which potentially confounds results by using standardised movement speeds (Greene & Williams, 1996; Heuninckx et al., 2004). Thus, the experimental study of Part 1 examined the attentional cost of maintaining coordination patterns applying individualised movement speeds. Part 2 of the research further investigated attentional resource allocation using electroencephalography (EEG) as a neurophysiological measure of central cost during performance of interlimb coordination in

older adults. Part 3 investigated the inhibition hypothesis for age-related changes in motor function focusing on cortical activity. The experimental study in Part 3 used transcranial magnetic stimulation (TMS) to measure inhibitory and facilitatory processes within the motor cortex during coordination of hand and foot movements.

Overview of the thesis

The introductory chapter (Chapter 1) outlined current views of motor function in older adults introducing the three main hypotheses advanced to explain age-related changes in motor function. The research was conducted in three phases (Part 1 to Part 3). Each of the three phases consists of a literature review of relevant issues and the empirical study.

Part 1 of the thesis starts with Chapter 2 reviewing age-related changes in interlimb coordination. From the reviewed studies it is suggested that when young and older adults are compared there is a need to equalize task difficulty by individualizing movement frequencies to control the effect of general slowing wit age. The subsequent section of Chapter 2 introduces recent findings on the interplay between attentional function and interlimb coordination followed by an overview of age-related changes in attention. Chapter 2 concludes with a summary of key points with a focus on the

importance of applying standardized task difficulty between individuals in the investigation of age-related changes in interlimb coordination. Chapter 3 describes and reports the results of the first empirical study investigating age-related changes in inter-limb coordination and the associated attentional cost with task difficulty standardised between participants.

Part 2 of the research focused on the neurophysiological correlates of central resource allocation during interlimb coordination in older adults. Chapter 4 outlines the changes with advancing age in cortical activation and cognitive functions during motor task performance. Subsections in Chapter 4 include an overview of the neurophysiological technique Event Related Potentials (ERPs) and age-related changes in the P3b component of the ERP, followed by a section outlining the advantage of utilizing ERPs for the investigation of age-related changes in interlimb coordination. Chapter 5 describes the second empirical study examining age-related changes in central resource allocation during interlimb coordination utilizing ERPs.

Part 3 of the research investigated motor cortex activity during interlimb coordination in older adults. The first section of Chapter 6 provides a review of age-related changes in general inhibitory function and stresses the significance of investigating intracortical inhibitory processes to study interlimb coordination using transcranial

magnetic stimulation (TMS). The subsequent sections in Chapter 6 give an overview of the TMS technique followed by a review of age-related changes in intracortical inhibition. The last section of Chapter 6 introduces findings of recent studies investigating intracortical inhibition in the context of interlimb coordination. Chapter 7 describes the third empirical study using TMS to investigate excitatory and inhibitory processes during interlimb coordination in young and older adults.

In Chapter 8, an overall summary of the main findings from the three empirical studies and a discussion of the age-related changes in interlimb coordination are presented.

Chapter 2 Literature Review (Part 1)

Age-related Differences in Interlimb Coordination and Associated Attentional Cost

2.1 Effect of Aging on Interlimb Coordination

Basis of interlimb coordination

Everyday activities including walking, driving a car, playing a music instrument, tying shoelaces, or opening a bottle are movements involving coordination of several limbs. These coordination behaviours often require the regulation of the limbs in both amplitude (spatial) and duration (temporal) to meet specific task requirements (Wenderoth, Debaere, & Swinnen, 2004). Spatio-temporal control of limbs refers to the regulation of limbs in both spatial amplitude and temporal duration. There are spatio-temporal constraints, which regulate interlimb coordination and influence the performance of the coordination pattern (see review, Swinnen, 2002). For example with respect to a finger tapping task, temporal constraints explain the phenomenon that performance of tapping is most accurate and consistent when the fingers move at the same frequency (1:1) than at integer frequency ratios (1:2 or 1:3) or non-integer polyrhythmic ratios (2:3 or 3:5) (Wenderoth et al., 2004). Spatial complexity consists of two constraints, the egocentric and allocentric constraints. The egocentric constraint is linked to muscle homology (Figure 2.1a). When a task requires

bilateral movement of upper-limbs or lower-limbs towards and away from the body midline in the horizontal plane, the task can be performed most consistently and accurately when the limbs are moving in a mirror-symmetrical manner (in-phase) in which homologous muscles are simultaneously activated compared to limbs moving in a non-symmetrical manner (anti-phase). In contrast, the allocentric constraint operates when upper- and lower-limbs are moving either in the same or opposite directions (Figure 2.1b). Moving two limbs in the same direction (isodirection) is more stable than in the opposite direction (non-isodirection or antidirection) (Baldissera, Cavallari, & Civaschi, 1982; Kelso & Jeka, 1992; Serrien & Swinnen, 1997; Swinnen, 2002; Swinnen, Dounskaia, Verschueren, Serrien, & Daelman, 1995; Wenderoth et al., 2004). Furthermore, it has been shown that there is a favoured limb combination, that is, performing the non-isodirectional pattern with limbs on the same side of the body (ipsilateral) is more difficult than with limbs on opposite sides of the body (contralateral) (Hiraga, Summers, & Temprado, 2004, 2005; Meesen, Wenderoth, Temprado, Summers, & Swinnen, 2006).

In addition to the above mentioned spatiotemporal constraints, movement frequency is another factor which determines the quality of coordination performance (Wenderoth et al., 2004). With increasing movement frequency, an involuntary transition (phase transition)

at a critical frequency (CF) can be often observed from the non-symmetrical pattern for bimanual coordination and non-isodirectional pattern for upper- and lower-limb coordination to the more stable symmetrical and isodirectional patterns (Baldissera et al., 1982; Baldissera, Cavallari, Marini, & Tassone, 1991; Carson, Goodman, Kelso, & Elliott, 1995).

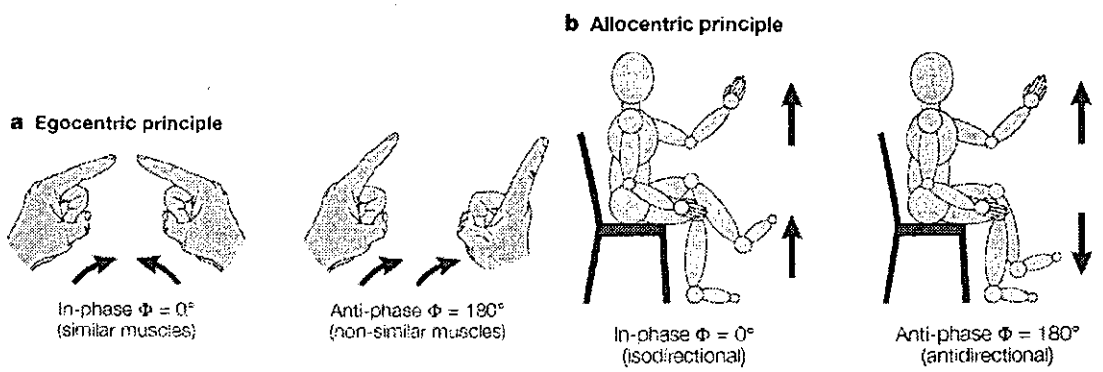


Figure 2.1 Basic coordination constraints: a. Egocentric and b. Allocentric. Φ: relative phase. (Adapted from Swinnen, 2002).

The neuromuscular mechanisms underlying the coordination of upper and lower limbs have been extensively investigated by Baldissera and Colleagues (e.g., Baldissera, Borroni, & Cavallari, 2000; Baldissera & Cavallari, 2001; Baldissera, Cavallari, & Tesio, 1994). Their findings indicate that when two different extremities (e.g., arm and leg) are involved in a coordination task performed at several movement frequencies, appropriate

timing of muscle activation is required to adjust for delays caused by the different mechanical characteristics of the two limb segments. For example, Baldissera and colleagues (Baldissera et al., 1994) investigated the relationship between onset of extensor carpi radialis (ECR) hand muscle activity and tibialis anterior (TA) leg muscle activity during both isodirectional and non-isodirectional cyclical coupling of the right hand and right foot. The EMG phase difference between the ECR and TA increased in response to an increment in movement frequency by increasing the ECR muscle burst lead relative to the TA muscle bust. This form of adjustment reflected the relatively larger influence of inertia on the hand than the foot (Baldissera et al., 2000). That is, the phase lag between hand movement and ECR burst developed more dramatically relative to the phase lag between foot movement and TA burst with increases in movement frequency. The involvement of inertia was demonstrated by applying two different types of loading on the hand including an elastic or inertial load. The load manipulations were clearly fitted to the second-order model. That is, inertial loading induced an immediate and steep decay of the phase lag between EMG onset of the ECR and hand movement as a response to increased frequency, while elastic loading delayed the phase lag development (Baldissera & Cavallari, 2001). Thus, during an interlimb coordination task using two limbs which have different

mechanical properties, such as the hand and foot, to maintain coordination the phase relationship between muscle activation and movement must change with increases in movement frequency. Of particular interest in the present study was to investigate whether the ability to modulate the relationship between muscle activation and movement onset is affected by the aging processes.

Age-related changes in interlimb coordination

In studies investigating age-related changes in inter-limb coordination, little age-related decline has typically been found with tasks that require performance at a slow movement frequency (Greene & Williams, 1996; Heuninckx et al., 2004), symmetrical patterns during bimanual coordination (Greene & Williams, 1996; Lee et al., 2002; Wishart et al., 2000), and isodirectional coordination between upper- and lower-limbs (Serrien et al., 2000). These results are explained by the nature of symmetrical/isodirectional coordination patterns and general motor slowing. That is, the symmetrical pattern for bilateral coordination and the isodirectional pattern with upper- and lower-limbs represented preferred intrinsic coordination tendencies that are more automatically processed than non-symmetrical and non-isodirectional patterns, respectively (Kelso & Jeka, 1992; Serrien & Swinnen, 1997; Swinnen, Dounskaia, Verschueren, Serrien, & Daelman, 1995). Over the

course of aging these preferred intrinsic coordination tendencies are strengthened. Wishart et al. (2000) found declined performance of a bimanual coordination task in older adults during the asymmetrical coordination pattern, particularly at the higher movement speeds (1.5 Hz and 2.0 Hz), but not during the symmetrical coordination pattern. Furthermore, it has been shown that the critical frequency (CF), which is the maximum frequency at which the coordination pattern can still be accurately performed, is significantly lower in older adults compared to younger adults (Greene & Williams, 1996; Heuninckx et al., 2004). For example, during non-isodirectional hand and foot coordination, Heuninckx and colleagues (2004) found that the majority of older adults in the sample showed a spontaneous phase shift to the more stable isodirectional pattern at 1.15 Hz, whereas for younger adults a phase transition did not occur until a frequency of 1.77 Hz. A similar result has been reported in a study of bimanual coordination (Greene & Williams, 1996) with older adults having a lower CF (1.51 Hz) than younger adults (2.16 Hz).

A problem in many previous studies investigating age-related changes in interlimb coordination is that fixed movement frequencies were used requiring both older and younger adults to perform a task at the same frequencies. In these studies age-related deteriorations were typically observed when performing the more difficult patterns, i.e.,

non-isodirectional/anti-phase at high movement frequencies. However, the interpretation of results from studies using fixed frequencies should be made with caution since it is possible that older adults performed poorly simply because at the higher movement frequency they are closer to the critical frequency for phase transition than younger adults. It has been suggested that the process of aging slows down cognitive, motor, neural, and perceptual speed (Hunter et al., 2001; Morgan et al., 1994, Salthouse, 1991; 1996). Thus, at the same movement frequency maintaining the coordination pattern may be more difficult for older than younger adults. As mentioned previously, the maximal movement frequency at which older adults can maintain a coordination pattern is lower than for younger adults (Greene & Williams, 1996; Heuninckx et al., 2004). This age difference in CF indicates that the level of task difficulty at fixed movement frequencies would not be uniform for older and younger adults due to the general motor slowing with advancing age. The finding by Lee and colleagues (Lee et al., 2002) that older adults sacrificed movement speed during performance of a bimanual coordination task in order to maintain the required coordination suggests that older adults may spontaneously adjust task difficulty. Other studies have similarly reported that older adults tend to stay at a slower speed to maintain accuracy and stability of the task rather than speeding up the movement which often causes disturbance

of the coordination (Serrien et al., 2000; Wishart et al., 2000). As a result of compromising speed, older adults occasionally outperform younger adults (Lee et al., 2002). These findings suggest that in comparing younger and older adults on tasks involving motor coordination movement frequency should be adjusted to ensure equal levels of task difficulty between groups.

The speed of a functional movement task is also dependent on an individuals' ability to accelerate body segments (Evans, 2000; Ploutz-Snyder, Manini, Ploutz-Snyder, & Wolf,. 2002). Muscular power, defined as rapid force development, has a great impact on the acceleration of body parts. Thus, a decline of muscular power with advancing age is regarded as playing an important role in the decline of functional movement speed (Evans, 2000) and task performance including the control of postural sway (Izquierdo, Aguado, Gonzalez, Lopez, & Hakkinen, 1999).

Another factor influencing motor performance is the effective coordination of muscle groups. For example, during a balance control task, temporal demands to maintaining balance over time requires rapid activation of task relevant muscles as well as appropriate coordination of muscle groups. In older adults, patterns of activation of multiple muscles are distinct from younger adults (see review, Barry & Carson, 2004).

Compared to younger adults, older adults exhibit a greater tendency of coactivation of agonists and antagonists muscles (Hortobagyi & DeVita, 2000; Klein, Rice, & Marsh, 2001; Macaluso et al., 2002; Spiegel, Stratton, Burke, Glendinning, & Enoka, 1996). The increased coactivation of agonists and antagonists muscles is thought to contribute to joint stiffness and is beneficial in avoiding disturbances to joint position from external forces (Milner, 2002). However, increased joint stiffness through coactivation of agonist and antagonist muscles often degrades the performance of functional movement tasks such as stair descent (Hortobagyi & DeVita, 2000). Thus, there is some evidence of distinct age differences in the coordination of groups of muscles within a limb during motor tasks. However, age-related changes in the coordination of groups of muscles in different limbs have not been previously investigated.

In addition to motor slowing and neuromuscular changes with advancing age, it has been suggested that age-related changes in cognitive functions, particularly attentional function, can have a considerable influence on motor performance in older adults (Woollacott & Shumway-Cook, 2002). The following sections outline age-related changes in attentional function and discuss the importance of attentional control for interlimb coordination.

2.2 Age-Related Changes in Attention

Theoretical approaches to attention and aging

The term 'Attention' has been operationally defined in various ways depending on the theoretical approach adopted by the researcher. Kahnemans's (1973) resource theory posits attention as the fuel or processing resource for other cognitive processes. An assumption of this approach is that in order to perform a task it is necessary to access a limited capacity pool of resources. In this sense, if there are two or more tasks to be performed at the same time and the aggregate of the cost to perform these tasks exceeds the capacity, performance of one or both tasks will be compromised (Neumann, 1984; Shumway-Cook & Woollacott, 2000; Wickens, 1989). In the context of resource theory, aging is characterized by a reduction of the attentional resources available for tasks. Therefore, resource theory has suggested that an age-related change of attentional capacity is a primary cause of behavioural insufficiency in older adults (McDowd & Shaw, 2000). Influenced by resource theory, Salthouse (1993; 1996) developed a theoretical approach to explain the link between attention and aging, named the speed processing approach. A key feature of this approach is that processing speed is considered as a component of the

resource available for information processing rather than assuming that processing speed is a separate component in the entire process of information processing (McDowd & Shaw, 2000). The processing speed hypothesis suggests that processing speed as a single factor can account for a considerable proportion of age-related changes in cognitive processes (McDowd & Shaw, 2000). Evidence for the processing speed perspective has been mainly derived from statistical analyses that remove the variance in the component of processing speed before analyzing the relation between age and cognitive task measures (Salthouse, 1996). In a series of studies it was consistently demonstrated that processing speed was a major contributor to the age-related decline observed in a variety of cognitive memory tasks (for more detail see Salthouse, 1996).

Other related theories that have been advanced to explain age-related attentional changes are inhibitory deficit theory and executive control theory (Hasher & Zacks, 1988; McDowd & Shaw, 2000). In inhibitory deficit theory[2], attention serves as a function which selectively processes task relevant information, while suppressing irrelevant information processing and responding (Hasher & Zacks, 1988). In older adults, declined inhibitory

[2] Note that inhibitory function in the context of attentional control is hypothesised recent to be mediated by frontal areas of the brain (Kramer et al., 1994). It is not synonymous with cortical inhibition measured with TMS.

function with age is reflected in declined performance in attentional tasks. The inhibitory hypothesis has been evaluated by a number of studies using cognitive and motor tasks which require participants to ignore or suppress the processing of task irrelevant information (Balota & Black, 1997; Balota & Ferraro, 1993; Brosseau, Potvin, & Rouleau, 2007; Falkenstein, Hoormann, & Hohnsbein, 2002; Kramer et al., 1994; Logan, 1994; Potter & Grealy, 2006, 2008). For example, Potter and Grealy (2008) investigated age-related change in the ability to inhibit a prepotent motor response during an ongoing action.. The ongoing action task was copying horizontal hand movements (moving a hand from left to right repeatedly) made by the experimenter as closely as possible, but to ignore any vertical hand movements. As expected, older adults showed more errors due to a failure to inhibit incorrect movements than young adults. Brosseau , Potvin, and Rouleau (2007) using a motor skill learning paradigm also demonstrated that older adults have difficulty learning a mirror tracing task requiring suppression of incorrect responses. In contrast, older participants showed a similar learning rate to younger adults on a task requiring the tracking of a moving target (Pursuit tracking task). Although the tracking task involved similar coordinated movements to the mirror tracing, the tracking task required much less inhibitory control. It was hypothesised that the slower leaning rate on the mirror tracking

task in older adults was due to a breakdown of inhibitory control. Specifically, the motor system failed to inhibit incorrect responses produced by inconsistent visuo-motor information in the mirror tracking task. The existence of a frontal inhibitory system has been recently demonstrated in fMRI studies (de Zubicaray, Andrew, Zelaya, Williams, & Dumanoir, 2000; Garavan et al., 1999; Konishi et al., 1999; Liddle, Kiehl, & Smith, 2001). Using event-related potentials (ERPs), Falkenstein and colleagues (Falkenstein, Hoormann, & Hohnsbein, 2002) investigated age-related changes in inhibitory control during a Go/Nogo task. For Go-trials older adults demonstrated slower RT and longer latency of the P300 component of the ERP which indexes allocation of attention than younger adults. It was hypothesised that the slower RT in older adults was due to a declined ability of inhibitory control which delayed the decision whether to respond or inhibit the motor response.

A related theory is executive control theory which regards attention as one of the cognitive functions that is controlled by a superordinate system (McDowd & Shaw, 2000). In this theory, inhibitory function is also considered as one of the subordinate functions of executive processes (Verhaeghen & Cerella, 2002). Verhaeghen and colleagues (Verhaeghen, Kliegl, & Mayr, 1997) suggested that executive control theory complements

the processing speed hypothesis in understanding attention in older adults. That is, to perform a complex cognitive task the coordination of basic components in working memory is essential and often these tasks require appropriate responses to be made in a given time frame. An important contribution of inhibitory theory and the executive control approach to the study of aging is that the theories make a link between anatomical structure and attentional control, suggesting that age-related decreases in cognitive function are associated with decreased frontal lobe function (see review West, 1996). Neuroimaging research has also supported this notion reporting increased activation in frontal regions in older adults who performed a divided attention task as well as young adults (Heuninckx et al., 2005; Heuninckx et al., 2008; Madden, Turkington, Provenzale, Hawk, & Hoffman, 1997).

In summary, these theoretical approaches provide specific views with regard to the mechanisms underlying the decreased ability in attentional control with age. That is, resource theory considers reduced attentional capacity itself as a main cause, while processing speed theory assumes declined processing speed in older adults. In contrast, inhibitory and executive control theories suggest that changes to a superordinate system with advancing age are mainly responsible for the declined performance in attentional tasks

by older adults. These theoretical frameworks have been suggested as explanations for age-related changes in attentional function and have contributed to the integration of the findings from age differences research. The aforementioned theories of attention deal with the basic mechanisms underlying different functions of attention. The following section outlines the functional perspective of attention.

Functional perspective of attention in aging

The functional perspective of attention by McDowd and Shaw (2000) provides an effective way to understand the detail of attentional function. Attention is categorized by its function into selective, divided, switching, or sustained attention. In selective attention tasks participants need to allocate their attention only on relevant information, ignoring distractors, e.g., visual search, stroop task, and negative priming. Although there are a vast number of studies reporting greater susceptibility to interference in older adults compared to younger adults (see review McDowd & Shaw, 2000), a number of findings suggest a general slowing account for the poor selective attention task performance in older adults rather than deficit in attentional capacity (Salthouse & Meinz, 1995; Salthouse, Toth,

Hancock, & Woodard, 1997; Verhaeghen & De Meersman, 1998a, 1998b).

In contrast, divided, switching, and sustained attention studies have shown a clearer picture with divided attention tasks especially demonstrating consistent age-related changes (Craik & Bialystok, 1977; Verhaeghen & Cerella, 2002). Furthermore, age differences in divided attention cannot be accounted for by general slowing alone (Kramer, 1996; Salthouse, Fristoe, Lineweaver, & Coon, 1995) since disproportionate age declines have been found on complex tasks. There is a general agreement that factors such as task difficulty and task similarity are largely responsible for age differences in divided attention tasks requiring concurrent performance of two tasks (McDowd & Shaw, 2000). These factors appear to underlie two types of interference, capacity and structural interference (Schmidt & Lee, 1999), which result in performance trade-offs. Capacity interference occurs when the greater proportion of available resources is allocated to one of the tasks, resulting in fewer attentional resources for the other task. In contrast, structural interference stems from processing in tasks sharing similar physical and neurological structures or processes (Navon, 1985; Navon & Miller, 1987). An example of capacity interference comes from a study by Lindenberger and colleagues (2000) in which younger and older adults memorized word lists while walking on two narrow tracks differing in path

complexity. Both young and older adults showed a reduction in speed and accuracy of walking in dual-task compared to single-task conditions. Furthermore, age-differences were greater in the dual-task conditions, especially on the more complex track. The greater age-difference in the more difficult condition suggested a reduced attentional capacity in older adults compared to young adults.

In contrast, task similarity has been associated with structural interference. According to the structure-specific model of dual-task performance (Wickens, 1984), performance in dual-task situations depends on the extent to which the two tasks share similar stages of processing, codes of processing, or input-output modalities. Based on this model, Tsang and Shaner (1998) examined age-related changes in the dual-task performance of a manual horizontal-line tracking task and either a vertical-axis tracking task, a spatial orientation task, or a memory task. The structural similarities between these task combinations varied and the extent of these similarities were clearly reflected in the performance of the horizontal-line tracking task. That is, the two tracking tasks shared similar processing structures to a greater extent than the spatial orientation task, while the memory task had a distinct processing structure to the other tasks. Furthermore, age differences increased with task similarity. That is, the closer the structural similarities were

between tasks, the greater the age differences in performance.

Similar to divided attention tasks, switching and sustained attention tasks have demonstrated age-related decrements. Unlike divided attention, in terms of the factors that mediate the difference, general slowing can account for the declined performance of older adults in switching attention tasks (Salthouse, Fristoe, McGuthry, & Hambrick, 1998) and sustained attention tasks (Salthouse, 1993).

In summary, general slowing appears to account for a large proportion of age-related attentional decrements. In this sense, the processing speed approach by Salthouse (1991; 1996) well explains the phenomenon, however, especially in divided attention tasks there are other factors which may modulate the difference between older adults and younger adults. The particular interest in the present research was to assess the required attentional cost of motor coordination in older adults utilizing a dual-task paradigm.

2.3 Attention and Interlimb Coordination in Older Adults

Recently a link has been drawn between the stability of a movement pattern and the central cost required to maintain that pattern (Temprado, Chardenon, & Laurent, 2001). A dual-task methodology, involving the concurrent performance of two tasks, is often

utilized to assess the resource demands of cognitive tasks. One of the tasks is designated as the primary task and participants are instructed to maintain good performance on that task while performing the other task, called the secondary task, to the best of their ability. Performance on the secondary task is taken to reflect the attentional demands of the primary task (Craik & Anderson, 1999). Temprado and colleagues conducted a series of experiments examining the role of attentional processes in the coordination of bimanual movements using a discrete probe reaction time task as a secondary task. Their main findings were that spontaneous transitions from a less stable to a more stable movement pattern can be delayed by manipulating attention (Monno, Chardenon, Temprado, Zanone, & Laurent, 2000), and that attentional cost and pattern stability covary (Zanone, Monno, Temprado, & Laurent, 2001). That is, the more stable behavioural states of the system (e.g., in-phase) require less attention to maintain than less stable states (e.g., anti-phase). Furthermore, increasing the oscillation frequency of a motor pattern reduces its stability and thereby increases the attentional load needed to maintain the pattern (Temprado et al., 2001). Similarly, Hiraga and colleagues (Hiraga et al., 2004, 2005) investigated the role of attention in the coordination of upper- and lower-limbs. In those studies the interplay between performance of a circle drawing task and attentional function was examined by

comparing symmetrical and non-symmetrical coordination patterns produced with contralateral and ipsilateral limb combinations. Probe RT, used as an index of attentional cost, was faster during symmetrical coordination pattern than non-symmetrical coordination patterns, suggesting that the less stable non-symmetrical coordination pattern required more attentional cost compared to more stable symmetrical coordination pattern. The results extended the previous findings of Temprado and colleagues (Monno et al., 2000; Zanone et al., 2001) demonstrating the contribution of attention in the stabilization of coordination patterns involving the coordination of upper- and lower-limbs.

In older adults, even relatively highly practiced and maintained behaviours such as walking (e.g., Lajoie et al., 1996; Sparrow, Bradshaw, Lamoureux, & Tirosh, 2002) and bimanual coordination (Sparrow, Lay, & O'Dwyer, 2007) demand more attention compared to younger adults. Also attention plays a greater role in controlling posture in older adults (see review, Woollacott & Shumway-Cook, 2002). Thus older adults may achieve similar levels of motor performance as younger adults, but at an increased attentional cost. Tee (2002), for example, using the dual-task paradigm, showed that older adults required more attention to perform a bimanual circling task to the same level as younger adults. Similarly, Sparrow and colleagues (Sparrow, Parker, Lay, & Wengier, 2005) used a dual-task

paradigm to investigate age-related changes in attentional demands during extended practice on a high-energy two-hand coordination task requiring either an easy (180°) or difficult (90°) relative phasing between the hands. Older adults showed higher attentional demands than younger adults for both patterns throughout practice with greater attentional cost evident during practice of the 90° pattern which they were not able to learn. It was hypothesised that the higher attentional cost of the difficult coordination was due to the necessity to resist attraction to the more stable anti-phase coordination. However, as both groups of participants were required to perform the high-energy task at the same rate, it is possible that differences in task difficulty between younger and older participants may account for the observed differences in attentional demands rather than age-related changes in the performance of the interlimb coordination task. Some support for this view comes from the finding that older adults had significantly higher heart rates during task practice suggesting greater exertion (Sparrow et al., 2005).

A related study by Heuninckx et al. (2004), which investigated the age-related difference in coordination of ipsilateral upper- and lower-limbs in a dual-task situation, found less stable coordination performance in both younger and older adults when participants performed the interlimb coordination task and an attentional task concurrently.

The coordination task involved the performance of isodirectional and non-isodirectional coordination patterns with ipsilateral limbs at two movement frequencies (1.0 and 1.5 Hz). The concurrent attentional task was a line detection task, which required participants to match a series of line figures with a previously presented target figure and report the number of matches at the end of a trial. A pronounced decrease in coordination performance in older adults was observed at the 1.5 Hz frequency. It was argued, however, that because of different critical frequencies (See section 2-1), it was more appropriate to compare the performance of older adults at 1 Hz with that of younger adults at 1.5 Hz. When this comparison was made the age-related differences in interlimb coordination performance disappeared. Although, the authors argued that decreased attentional capacity was not the primary source of the declined interlimb coordination performance with age, other studies (Hiraga et al., 2004; 2005; Monno et al., 2000; Temprado et al., 2001; Zanone et al., 2001) showing declined interlimb coordination performance in the dual-task compared to single-task conditions strongly suggested that attention influences the performance of interlimb coordination tasks in the aged.

2.4 Summary

Previous studies suggest that there are age-related changes in attentional function and declines in motor coordination. At the same time, manipulation of the frequency at which the motor task is performed is possibly crucial when it comes to the comparison between younger and older adults since general motor slowing may create a situation where older adults find a certain movement frequency challenging, while younger adults do not. As task difficulty has been shown to increase age-related differences in task performance (McDowd & Shaw, 2000), demonstrated age differences in motor tasks reported in studies using fixed movement speeds may primarily reflect general motor slowing which has been observed in a variety of "speeded tasks" (e.g., reaction time) (Salthouse, 2000). Thus, the systematic manipulation of movement speed while equating task difficulty on an individual rather than a group level is necessary to fully evaluate age-related changes in motor coordination and associated attentional costs.

The following chapter (Chapter 3) includes the study which is in preparation for submission as a journal article.

Chapter 3 Experimental Study 1

3.1 Introduction

Previous studies investigating age-related changes in interlimb coordination have typically observed no age differences when an symmetrical pattern with two hands or an isodirectional pattern with the upper- and lower-limbs are performed, particularly at slow movement rates (Greene & Williams, 1996; Heuninckx et al., 2004; Lee et al., 2002; Serrien et al., 2000; Wishart et al., 2000). This is possibly because symmetrical and isodirectional patterns are more automatically processed than asymmetrical and non-isodirectional patterns (Lee et al., 2002).

Studies showing age-related interlimb coordination deficits have often employed fixed movement frequencies, requiring both older and younger adults to perform at the same frequencies, with age-related impairments being observed when non-isodirectional patterns are performed at high frequencies. However, this finding does not necessarily imply that older adults are less coordinated than younger adults. As there is a strong evidence of a general motor slowing with advancing age (e.g., Hunter et al., 2001; Morgan et al., 1994), applying the same movement frequencies to younger and older groups may cause unequal levels of task difficulty for the two age groups. This hypothesis is supported

by the finding that older compared to young adults generally have a lower critical frequency (CF) at which anti-phase or non-isodirectional coordination patterns can no longer be maintained accurately (Greene & Williams, 1996; Heuninckx et al., 2004). Furthermore, Heuninckx and colleagues (2004) observed no age differences in the coordination of hand and foot movements after a movement frequency adjustment was applied. These findings suggest that the effect of aging on movement coordination should be investigated with task difficulties standardized for each individual.

Another factor which has been shown to affect the stability of motor coordination is attention. It has been suggested that older adults require more attention in performing interlimb coordination tasks, especially difficult patterns, i.e., anti-phase and non-isodirectional coordination patterns (e.g., Lee et al., 2002; Sparrow et al., 2005). On the other hand, as mentioned previously, Heuninckx and colleagues (2004) suggested that a reduction in attentional capacity with aging was not the main cause of age-related decreased non-isodirectional coordination performance.

Given the conflicting results evident in previous research, a major aim of the current experiment was to further examine the relationship between aging, attention, and interlimb coordination. In particular, the performance of younger and older adults was compared on a

coordination task in which task difficulty was equated at an individual rather than a group level. It was hypothesized that age-related differences in performance during non-isodirectional coordination between upper- and lower-limbs would only be observed at frequencies close to an individual's predetermined critical movement frequency

A second aim was to investigate aging effects on interlimb coordination at the neuromuscular level. To our knowledge, no previous studies have investigated age-related changes in interlimb coordination at the neuromuscular level by measuring the temporal relationship between activations of upper and lower limb muscles. It was hypothesized that the degeneration of muscle strength with advancing age would cause a more rapid development of the phase lag development between movement onset and muscle burst onset in response to increases in movement frequency in older adults. The phase relationships between muscles in the upper and lower limbs were investigated using Electromyography (EMG) to obtain further insight into age-related changes in interlimb coordination.

3.2 Method

3.2.1 Participants

Twenty-four healthy right handed volunteers participated in the study, including 12 older adults (6 males, 6 females, age, $M = 67.08$ years; range 60-75 years) and 12 younger adults (6 males, 6 females, age, $M = 21.33$ years; range 18-26 years). The Mini-Mental State Examination (Dick et al., 1984) was used to screen for cognitive deficits in the sample of older adults. A score of 23 or less is "Suggestive of cognitive impairment" (Dick et al., 1984, p.498). The average score of the older participants in this study was ($M = 28.82$, $SEM = 0.40$). All participants were free of any neurological defects, symptomatic cardiovascular disease, diabetes or hypertension. Written informed consent was obtained prior to participation in the study. Ethics approval for the study was obtained from the University of Tasmania Ethics Committee.

3.2.2 Apparatus

Participants were seated in a custom-made chair consisting of a steel frame with a wooden back support and padded seat. The chair had four aluminium levers against which participants' arms and legs were held using elastic bandages, which allowed independent flexion and extension motion of the forearms and lower legs in the para-sagittal plane.

Height adjustable footrests attached to the leg levers were used to support the lower legs. The position of each lever was fully adjustable such that the axis of rotation could be aligned coaxial with the elbow or knee joint. Limb position data were obtained using potentiometers coaxial with each lever's axis of rotation. The voltage output from the potentiometers was sampled at 500 Hz using a 12-bit A/D system and was recorded on a computer hard drive for analysis off-line. The raw position data were low-pass filtered with a cut-off frequency of 50 Hz using a dual-pass Butterworth filter. Custom written software (Microsoft Office Excel 2003) was used to derive and calculate kinematic and spatiotemporal coordination measures.

A computer placed approximately 1 meter in front of participants (at eye level) was used to present a visual metronome which was projected on the computer screen as a 10 cm diameter circle flashing (at the desired movement frequency) with a duration of 100ms. Auditory tones (1400 Hz computer-generated signals of 50 ms duration) presented via loudspeakers were used to investigate reaction time. Responses to these stimuli were recorded through a microphone attached to headphones on the participant's head. To examine patterns of muscle activity in upper and lower limbs, surface EMG electrodes for arm and leg muscles were placed parallel to the muscle fibres of biceps brachii (elbow

flexor) in the right upper arm and rectus femoris (knee extensor) in the right and left leg. EMG signals were band-pass filtered (10-300 Hz), and amplified (gain 1000-2000x) by a Grass Model 12 amplifier. EMG data were sampled at 2000 Hz by a 12-bit A/D converter (DATAQ system).

3.2.3 Procedure

Participants were asked to complete movements in time with the visual metronome. The task required concurrent cyclical flexion and extension movements at the knee and elbow with a 1:1 ratio. The starting position of the limbs was at approximately 90° flexion for the elbow and knee. One complete movement cycle (i.e., from peak flexion to extension and back to peak flexion) was to be performed between every metronome beat. No specific movement amplitude was required at either limb and participants were instructed to move their limbs at their preferred amplitude. There were two movement conditions requiring the cyclical coordination of either contralateral limbs (right arm and left leg) or ipsilateral limbs (right arm and right leg) using non-isodirectional movements, i.e., the arm and leg moved in opposite directions. The limbs not involved in a required task remained at rest.

Prior to the experimental session, critical frequencies (CF) for each limb combination

were determined for each participant in a series of metronome paced trials in which frequency was increased 0.25 Hz every 8 s from 1 Hz. The critical frequency was the rate at which participants were no longer able to produce the required coordination pattern. The observed CFs for older adults were lower for both the ipsilateral (M = 1.68 Hz, SEM = 0.09 Hz) and contralateral (M = 1.72 Hz, SEM =0.10 Hz) limb combinations than for younger adults (Ms = 1.83 Hz and 1.88 Hz; SEM = 0.05 and 0.06 Hz, respectively). A 2 (GROUP) x 2 (LIMB COMBINATION) ANOVA revealed that while the group main effect was not significant F (1, 22) = 1.98, p = .170, ηp^2= 0.08, the ipsilateral limb combination exhibited a lower CF than the contralateral limb combination, F (1, 22) = 4.41, p = .047, ηp^2= 0.17. Unlike previous studies (Greene & Williams, 1996; Heuninckx et al, 2004), in the current study the lower mean CF in older adults during the ipsilateral limb combination compared to younger adults was not statistically significant. This may be due to the large variability in older adults which was suggested by the marginally significant Leven's test of homogeneity of variance (p = .061)[3].

To ensure individual levels of task difficulty in younger and older adults, during the following experimental trials participants performed the ipsilateral and contralateral limb

[3] Since an application of the square root transformation to the data did not alter the results, the result using non-transformed data was presented.

coordination tasks at three imposed frequencies: 20, 60, and 100 % of their individually determined CFs. All frequencies were paced by the visual metronome. Participants were also asked to perform the coordination at their preferred frequency, defined as the frequency at which the task could be comfortably performed for long periods of time. For each limb combination, three trials were performed at each frequency under both single- and dual-task conditions, making 24 trials in total. The duration of each trial was 15 s.

To measure age-related changes in the attentional cost of interlimb coordination, a dual-task paradigm involving an auditory probe reaction time task was employed. During dual-task trials participants performed the interlimb coordination task, designated as the primary task and, at the same time responded to randomly presented auditory probe stimuli by voicing the word 'tone' as quickly as possible. The probe RT task was also performed as a single-task. Five tones were presented randomly during the 15 s trials with an inter-tone interval between 600 and 4000 ms.

3.2.4 Data Analysis and Measures

Relative phase measures. Estimates of relative phase were obtained using the following procedure. The amplitude within each half cycle (peak-to-valley, valley-to-peak) was

rescaled to the range [1, –1] resulting in a transformed displacement time-series approximating a cosine function. Continuous phase-angles (degree) for each limb were obtained by taking the arccosine of each point on the scaled time series; continuous relative phase was then simply the arithmetic difference of the phase-angles of the two limbs at each point (Matthews, Garry, Martin, & Summers, 2006). Circular statistics (Mardia, 1972) were utilized to calculate the mean relative phase and the standard deviation (SD) of relative phase. Absolute Error (AE) of relative phase was obtained as a measure of accuracy of the interlimb coordination by averaging the absolute deviation from the mean target relative phase (180°), while the standard deviation (SD) of relative phase was used as a measure of pattern stability. Heuninckx et al. (2004) defined an acceptable deviation from the required non-isodirectional pattern as less than 50° for AE and 30° for SD of relative phase, while Calvin and colleagues (Calvin, Milliex, Coyle, & Temprado, 2004), used the range of 180°±90° as acceptable performance. Based on these two previously used criteria, the current study only included in data analysis patterns produced with AE and SD of relative phase not exceeding 70° and 50° respectively. For older adults, a considerable percentage of trials did not meet these criteria. At 100 % of CF in the ipsilateral limb coordination 30 % of the trials in the single- and 55 % of the trials in the dual-task were

excluded, while in the contralateral limb coordination at 100 % of CF 21 % of the trials in the dual-task condition were excluded. In all other conditions, the excluded trials were less than 10 %. In contrast, for younger participants, the most trials excluded from a condition was 6 %.

Spatiotemporal measures. Mean and standard deviations of the amplitude of limb movements were obtained by averaging the peak-to-peak amplitude of each cycle across the whole trial. Frequency deviation was calculated by subtracting the frequency produced by individual participants from the target frequency required for a particular condition. Movement frequency was defined as the time elapsed between two successive peaks in the position-time trace. The variability of movement frequency was assessed using the coefficient of variation to control the influence of absolute differences in standard deviation for each condition, defined as the standard deviation of movement frequency divided by mean movement frequency.

Attentional load measure. Vocal reaction time to probe stimuli was taken as a measure of attentional load during dual-task performance. Response times exceeding the range $M \pm 2SD$ in a condition were discarded since these responses were considered as a result of anticipation or error.

Phase relations between EMG and movement. The phase relationships between EMG and the corresponding limb movements were examined. The period between successive peaks in limb displacement was treated as one cycle. The EMG signal was rectified which is beneficial to preserve the temporal qualities of the motor units firing properties (De Luca, 1997). The onsets of muscle bursts were determined by a visual inspection with reference to the kinematic data to ensure the muscle burst onset preceded the ensuing movement. The period between an onset and following onset was treated as one cycle and expressed in degrees. The phase relationship between movement (at the knee and elbow) and the corresponding muscle burst onset (i.e., the rectus femoris and the biceps brachii bursts) was calculated as the average value across all cycles within a trial. 0° or 360° indicated that the onset of muscle activation occurred at the time of the peak amplitude of corresponding limb movement, while the value 180° indicated that the muscle burst occurred approximately at the time of movement onset in the corresponding limb (i.e., peak amplitude in the opposite half of the movement cycle).

EMG Phase-relation between upper limb and lower limb muscle activation. The EMG signals from the biceps brachii and rectus femoris muscles were used as a measure of coordination at the muscle level. Using the method described above to determine onsets of

burst activity in the two muscles, phase relationship between the two muscles, i.e., the onset of the biceps brachii activity in relation to that of the rectus femoris activity, was calculated. The value 180° indicated perfect non-isodirectional synchronization with respect to muscle activity. A value less than 180° indicated the onset of the rectus femoris occurred less than half a cycle prior to the biceps brachii, while values more than 180° indicated that the onset of rectus femoris was more than half a cycle prior to the biceps brachii. Figure 3.1 illustrates typical recording of arm and leg displacement and biceps brachii (BB) and rectus femoris (RF) EMG activity at 20, 60, and 100 % of CF.

3.2.5 Statistical Analysis

The data were examined using repeated measures ANOVAs applying Huynh-Feldt epsilon corrections when necessary and Tukey HSD test for post-hoc analyses were applied when appropriate. Partial η^2 (ηp^2) values were provided as a measure of effect size. An effect size of 0.01 is considered small, 0.06 medium and 0.14 and higher large (Sink & Stroh, 2006). Factors were GROUP (younger, older), LIMB (arm, leg), LIMB COMBINATION (ipsilateral, contralateral), TASK (single, dual), and FREQUENCY (20, 60, 100 % of CF, Preferred). In all figures error bars indicate standard error of the mean (SEM).

STATISTICA 7.1 software (StatSoft, Inc., OK, USA) was used for statistical analysis.

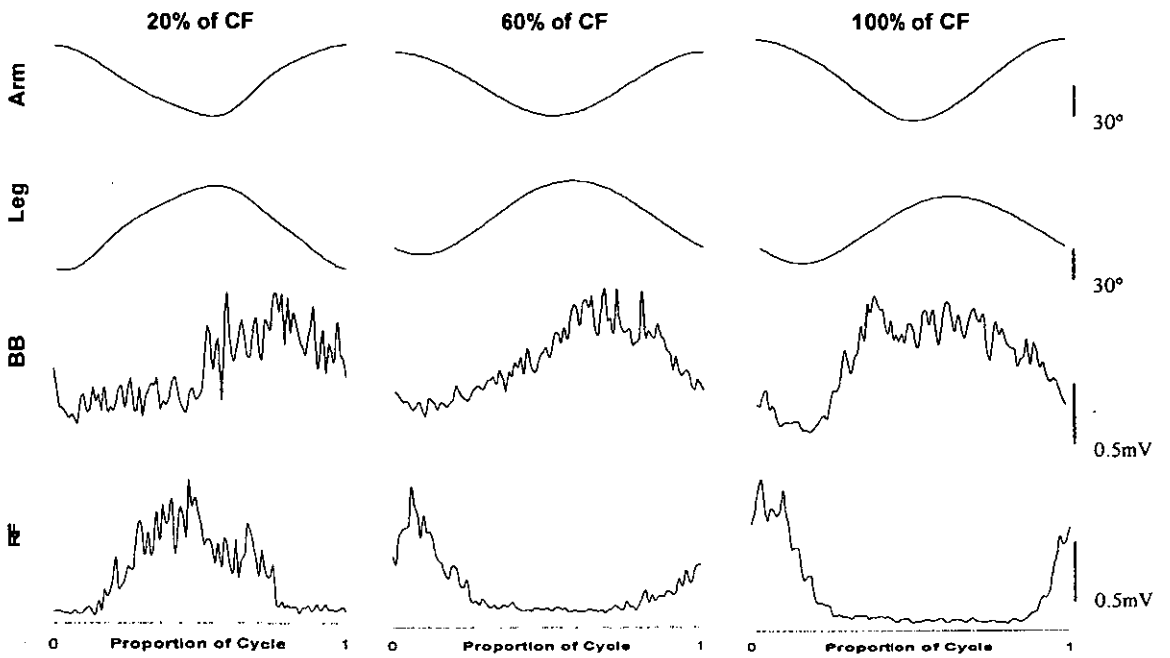


Figure 3.1 Arm and leg displacement and biceps brachii (BB) and rectus femoris (RF) EMG activities at 20, 60, and 100 % of CF.

3.3 Results

As age-related changes in interlimb coordination were of primary interest in the present study, all main effects and only interactions involving GROUP as a factor will be reported. Results of all statistical analyses are presented in Appendix D (in the attached compact disk (CD)).

3.3.1 Kinematic measures

Observed movement frequency. The observed movement frequency for older adults was generally slower across frequencies (60 % of CF, M = 1.06 Hz, SEM = 0.02 Hz; 100 % of CF, M = 1.35 Hz, SEM = 0.03 Hz; Preferred, M = 0.83 Hz, SEM = 0.02 Hz), than younger adults (60 % of CF, M = 1.13 Hz, SEM = 0.01 Hz; 100 % of CF, M = 1.67 Hz; Preferred, M = 1.03 Hz, SEM = 0.02 Hz) with the exception of 20 % of CF (older group, M = 0.45 Hz, SEM = 0.01 Hz; younger group, M = 0.39 Hz, SEM = 0.02 Hz). In relation to the required CF percentages (20, 60, 100) movement frequency, older adults performed the coordination task at 27 % (SEM = 2.0 %), 63 % (SEM = 2.5 %), and 80 % (SEM = 3.2 %) of CF, whereas young adults moved their limbs at 21 % (SEM = 0.2 %), 61 % (SEM = 0.5 %), and 91 % (SEM = 3.9 %) of CF.

Preferred Frequency. An analysis of the frequencies chosen by participants in the preferred frequency trials showed only a significant main effect of GROUP, F (1, 22) = 10.14, p = .004, ηp^2= 0.32. Older adults exhibited a lower (M = 0.83 Hz, SEM = 0.02 Hz) preferred frequency than younger adults (M = 1.03 Hz, SEM = 0.02 Hz). Interestingly, the preferred frequencies adopted by older adults corresponded to 47.6 % of the predetermined CF in

ipsilateral limb combination and 50 % of predetermined CF in the contralateral limb combination, while for younger adults the percentages were 56.8 % and 54.8 % of predetermined CF, respectively.

Frequency deviation. The mean deviations from the required frequencies were compared by employing a 2 x 2 x 2 x 2 x 3 (GROUP x TASK x LIMB x LIMB COMBINATION x FREQUENCY (20, 60, 100 % of CF)) ANOVA with repeated measures on the last four factors. There was a significant main effect of TASK, $F(1, 22) = 13.86, p = .001, \eta p^2 = 0.39$, indicating that participants were closer to the required frequency during dual-task trials (M = -0.04 Hz, SEM = 0.01 Hz) than when the coordination task was performed on its own (M = -0.08 Hz, SEM = 0.01 Hz). There was also a significant main effect of FREQUENCY, $F(1.24, 27.27) = 43.38, p < .001, \eta p^2 = 0.66$, and a significant GROUP x FREQUENCY interaction, $F(1.24, 27.27) = 5.98, p = .005, \eta p^2 = 0.21$. While both groups showed a similar pattern, older adults demonstrated a tendency to go faster at 20 % of CF and slower at 100 % of CF than younger adults (see Figure 3.2).

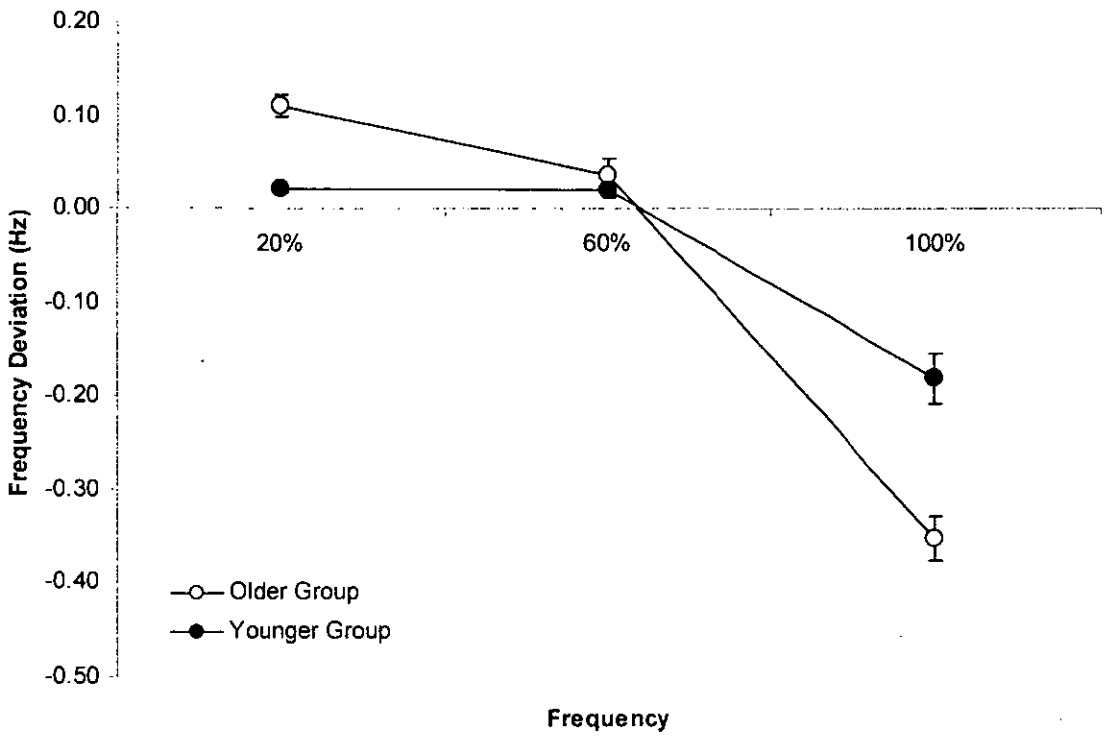


Figure 3.2 Mean frequency deviation for younger and older adults at each movement frequency.

Variability of Frequency. The coefficient of variation for frequency was analyzed by a 2 x 2 x 2 x 2 x 4 (GROUP x TASK x LIMB x LIMB COMBINATION x FREQUENCY (20, 60, 100 % of CF, Preferred)) ANOVA with repeated measures on the latter four factors. There was a significant main effect of LIMB COMBINATION, $F(1, 22) = 6.24$, $p = .020$, $\eta p^2 = 0.22$, indicating that frequency was more variable in the ipsilateral limb combination ($M = 7.62$ %, $SEM = 0.44$ %) than in the contralateral limb combination ($M = 6.19$ %, $SEM = 0.17$ %). There was also a significant main effect of TASK, $F(1, 22) = 14.33$, $p = .001$,

$\eta p^2 = 0.39$, indicating that frequency was more variable in dual-task conditions ($M = 7.65$ %, $SEM = 0.43$ %) than in single-task conditions ($M = 5.83$ %, $SEM = 0.15$ %). A significant main effect of FREQUENCY, $F(2.40, 52.83) = 23.10$, $p < .001$, $\eta p^2 = 0.51$, showed that 20 % of CF had a higher variability of movement frequency ($M = 9.99$ %, $SEM = 0.39$ %) than the other frequency conditions (60 %, $M = 6.26$ %, $SEM = 0.69$ %; 100 %, $M = 5.96$ %, $SEM = 0.27$ %; Preferred, $M = 5.40$ %, $SEM = 0.38$ %).

There was also a significant GROUP x FREQUENCY interaction, $F(2.40, 53.83) = 3.50$, $p = .020$, $\eta p^2 = 0.14$. Although, the two groups were comparable at all movement frequencies ($ps > .462$), post-hoc analysis revealed that the 20 % of CF condition exhibited significantly higher movement frequency variability than the other frequency conditions for older adults, whereas for younger adults the 20 % condition exhibited significantly higher variability than the preferred frequency condition, but not the other conditions (See Figure 3.3).

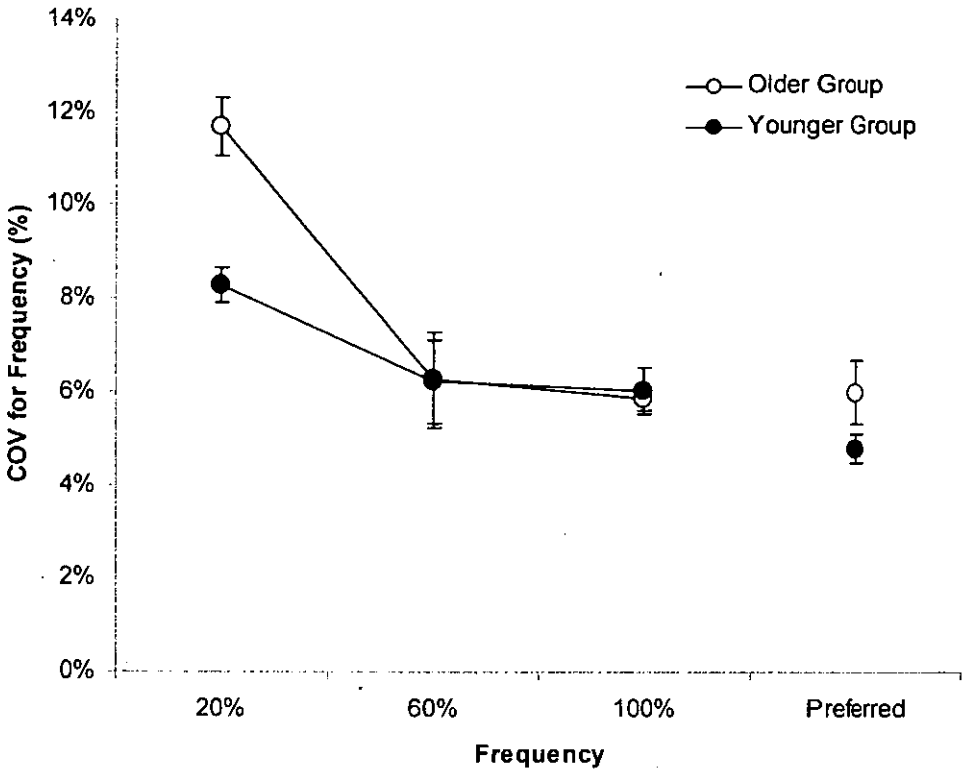


Figure 3.3 Coefficient of variation for movement frequency for younger and older adults at each movement frequency.

Movement Amplitude. The amplitudes of arm and leg movements were analyzed by a 2 x 2 x 2 x 2 x 4 (GROUP x TASK x LIMB x LIMB COMBINATION x FREQUENCY (20, 60, 100 % of CF, Preferred)) ANOVA with repeated measures on the latter four factors. There were significant main effects of TASK, $F(1, 22) = 16.08$, $p = .001$, $\eta p^2 = 0.42$, and LIMB COMBINATION, $F(1, 22) = 17.19$, $p < .001$, $\eta p^2 = 0.44$. Movement amplitudes were larger in single-task conditions ($M = 66.38°$, $SEM = 0.86°$) than dual-task conditions ($M = 62.91°$, $SEM = 0.92°$) and movements involving ipsilateral limbs were performed with larger

amplitudes (M = 67.15°, SEM = 0.86°) than movements involving contralateral limbs (M = 61.93°, SEM = 0.91°). There was also a significant main effect of FREQUENCY, F (1.72, 37.87) = 10.72, $p < .001$, $\eta p^2 = 0.33$, showing that amplitudes were larger at 20 % of CF (M = 69.54°, SEM = 0.1.14°) than at 60 % (M = 63.30°, SEM = 1.22°) and 100 % of CF (M = 60.04°, SEM = 1.39°). When moving at the preferred movement frequency, movement amplitude was also larger (M = 65.69°, SEM = 1.21°) than at 100 % of CF.

There were also interactions of GROUP x FREQUENCY, F (1.72, 37.87) = 6.28, $p < .001$, $\eta p^2 = 0.22$, and LIMB x FREQUENCY, F (2.48, 54.51) = 4.28, $p = .008$, $\eta p^2 = 0.16$, which were best interpreted in the context of the interaction of GROUP x LIMB x FREQUENCY, F (2.48, 54.51) = 9.97, $p < .001$, $\eta p^2 = 0.31$. As can be seen in Figure 3.4, for both upper- and lower-limbs and across all frequency conditions, with one exception, older adults made larger amplitude movements than younger adults. In the younger adult group the amplitude of both arm and leg movements decreased as frequency increased. In contrast, while older adults showed a similar pattern for arm movements, the amplitude of leg movements did not change significantly as a function of frequency. Thus, younger adults accommodated increases in required frequency by reducing the amplitude of both upper- and lower-limb movements, whereas older adults showed only a modulation of

upper-limb movement amplitudes. Importantly, within each frequency condition for both younger and older adults the amplitudes of arm and leg movements did not differ significantly.

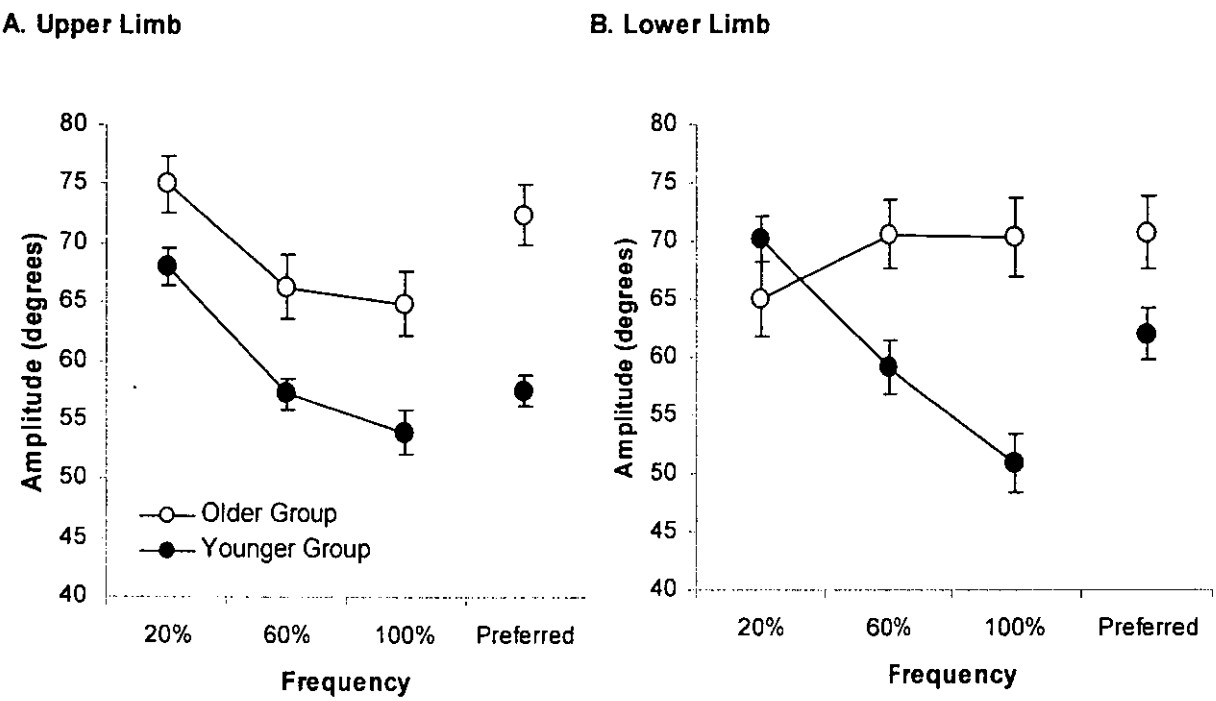


Figure 3.4 Mean movement amplitude of A. Upper- and B. Lower-limb for younger and older adults across movement frequencies.

There was also a GROUP x TASK x FREQUENCY interaction, $F(3, 66) = 3.07$, $p = .034$, $\eta p^2 = 0.12$, showing that the different amplitude patterns exhibited by younger and older adults were evident in both single- and dual-task performance (Figure 3.5). That is, for older adults amplitude was consistent across frequencies for both single and dual-task

conditions. For younger adults, amplitude was larger at 20 % of CF than other movement frequencies in both single and dual-task conditions.

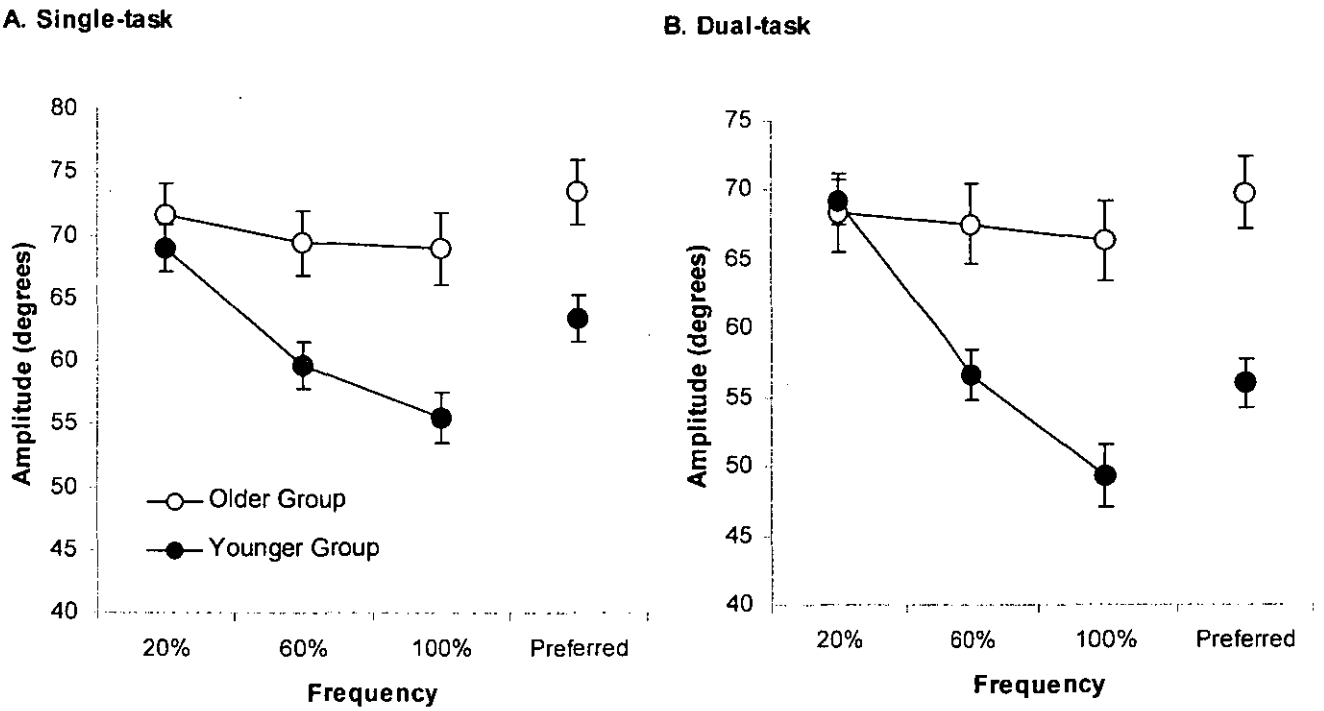


Figure 3.5 Mean movement amplitude of A. Single- and B. Dual-task for younger and older adults across movement frequencies.

Movement amplitude variability. There was a significant main effect of FREQUENCY, F (2.78, 61.12) = 8.63, p = .001, ηp^2= 0.28, a significant interaction of LIMB x FREQUENCY, F (2.95, 64.83) = 5.51, p = .002, ηp^2= 0.20, and a significant three-way interaction of GROUP x LIMB x FREQUENCY F (2.95, 64.83) = 3.88, p = .013, ηp^2= 0.15 (see Figure 3.6). For arm movements post-hoc Tukey tests showed no differences in amplitude variability between frequency levels for both younger and older adults. With

respect to leg movements, group differences were not significant in any of the conditions (*p*s >. 992). However, older adults showed a significant increase in amplitude variability with each increase in frequency ($p < .01$), whereas for younger adults increases in required frequency did not result in significant increases in amplitude variability ($p > .05$).

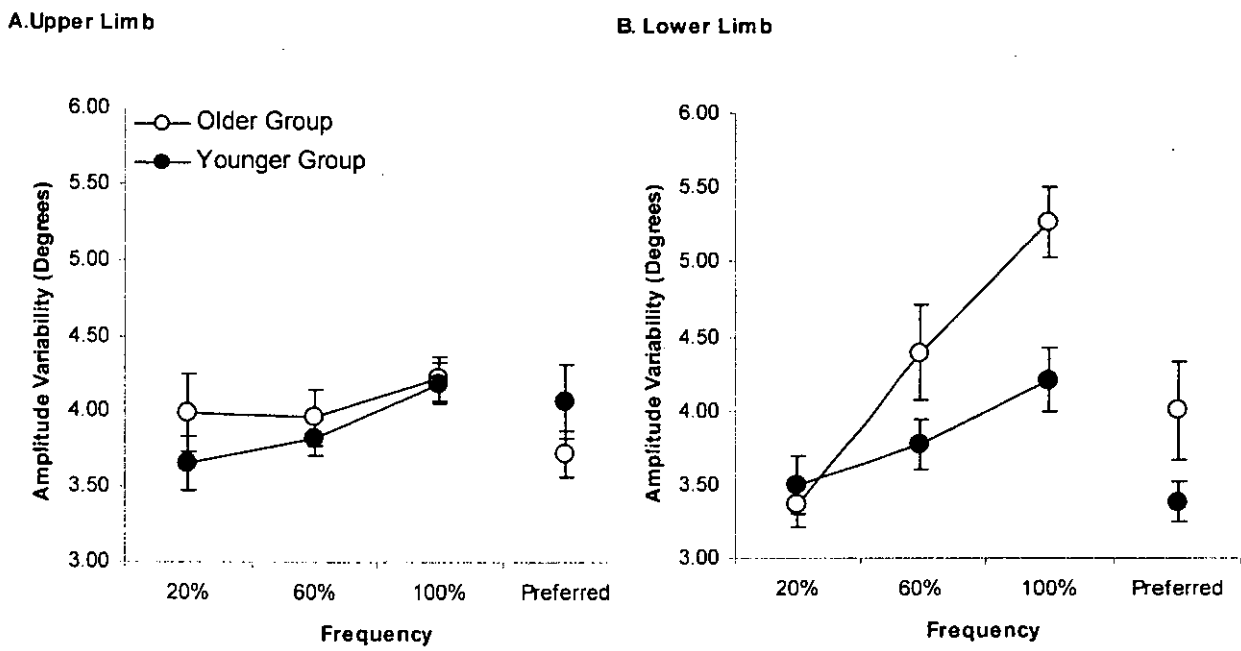


Figure 3.6 Amplitude variability of A. Upper- and B. Lower-limbs for younger and older adults across movement frequencies.

3.3.2 Relative phase measures

Absolute Error (AE) of Relative Phase. For mean absolute error of relative phase, there was a significant main effect of GROUP, $F(1, 22) = 8.61$, $p = .008$, $\eta p^2 = 0.28$, indicating that older adults showed greater deviation ($M = 19.95°$, $SEM = 1.22°$) from target relative phase

in comparison to younger participants (M = 13.01°, SEM = 0.94°). There was also a significant main effect of FREQUENCY, F (2.64, 58.16) = 66.21, p = .001, ηp^2= 0.75. As expected, interlimb coordination was significantly less accurate at 100 % of CF (M = 31.00°, SEM = 2.01°) than at the other movement frequencies (20 %, M = 7.67°, SEM = 0.62°; 60 %, M = 15.22°, SEM = 1.21°; Preferred, M = 12.04°, SEM = 0.94°) (ps < .001). No other significant main effects or interactions were evident.

Standard Deviation (SD) of Relative Phase. The standard deviation of relative phase was used as a measure of the stability of interlimb coordination. There was a significant main effect of GROUP, F (1, 22) = 19.95, p < .001, ηp^2= 0.48, suggesting that overall older adults had a lower coordination stability (M = 20.96°, SEM = 0.75°) than younger adults (M = 15.82°, SEM = 0.51°). There were also significant main effects of LIMB COMBINATION, F (1, 22) = 5.31, p = .031, ηp^2= 0.19, TASK, F (1, 22) = 7.90, p = .010, ηp^2= 0.26, and FREQUENCY, F (2.14, 47.04) = 40.57, p < .001, ηp^2= 0.65. Of particular interest was a significant three-way interaction of GROUP x TASK x FREQUENCY, F (1.91, 41.98) = 4.03, p = .027, ηp^2= 0.15. As can be seen in Figure 3.7, interlimb coordination performance of older adults was significantly less stable at 100 % of CF than

at other frequencies ($ps < .05$) for both single-task and dual-task conditions. Younger adults showed a similar pattern during single- and dual-task conditions with the 100 % of CF being significantly less stable than the other frequencies ($ps < .001$), except preferred movement speed condition during dual-task did not significantly different from 100 % of CF ($p = .40$). Furthermore, older adults evidenced a significant reduction in coordination stability during dual-task compared to single task trials at the highest frequency (100 % of CF, $p = .03$), whereas younger adults showed similar stability for single- and dual-task trials ($p = .87$). In summary, while both groups of subjects exhibited the expected loss of stability when performing at 100 % of CF compared to the other tested frequencies, for older adults concurrently performing a probe RT task resulted in a further loss of stability at the highest frequency.

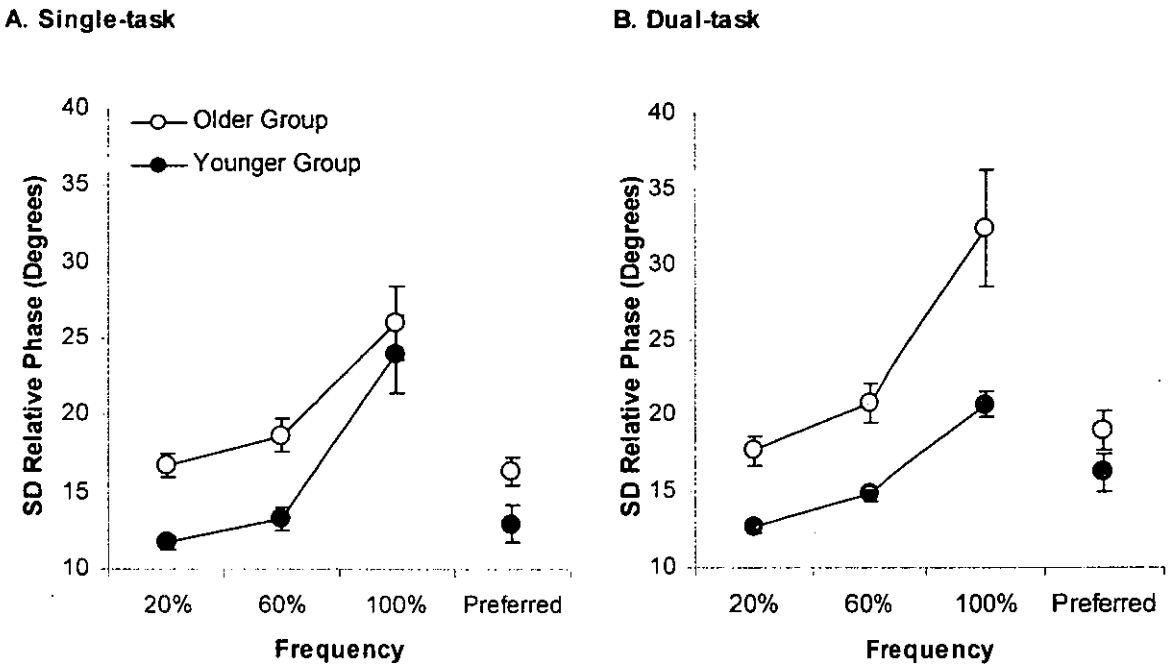


Figure 3.7 Standard deviation of relative phase for younger and older adults in A. Single- and B. Dual-task condition across movement frequencies.

3.3.3 Secondary task performance measure (probe RT)

Reaction Time. Vocal reaction time was examined as a measure of attentional cost using a 2 x 2 x 5 (GROUP x LIMB COMBINATION x CONDITION (single, 20, 60, 100 % of CF, preferred)) ANOVA. There was a significant main effect of GROUP, $F(1, 22) = 10.03$, $p = .004$, $\eta p^2 = 0.31$, with the older group showing slower reaction times ($M = 414.31$ ms, $SEM = 6.22$ ms) than younger adults ($M = 364.31$ ms, $SEM = 4.87$ ms). The significant main effect of LIMB COMBINATION, $F(1, 22) = 5.10$, $p = .034$, $\eta p^2 = 0.19$, suggested that the ipsilateral limb combination ($M = 395.70$ ms, $SEM = 6.32$ ms) required more attention to

perform than the contralateral limb combination (M = 382.93 ms, SEM = 5.68 ms). There was also a significant main effect of CONDITION, F (2.81, 61.82) = 36.07, $p < .001$, ηp^2= 0.62. Post-hoc analyses revealed, as expected, that when the reaction time task was performed on its own RT was significantly faster than in all the dual-task conditions. Within the dual-task conditions, moving the limbs at 20 % of CF resulted in significantly slower probe reaction times compared to 60 %, 100 % of CF, and preferred frequency.

3.3.4 EMG data

Phase relationship between EMG activation and movement. To investigate phase relationship between muscle activation patterns and movement, EMG activation onset relative to movement onset in that limb was examined using a 2 x 2 x 2 x 2 x 4 (GROUP x TASK x LIMB x LIMB COMBINATION x FREQUENCY) ANOVA. A significant interaction of GROUP x TASK, F (1, 22) = 7.69, p = .011, ηp^2= 0.26, indicated that older adults activated biceps brachii and rectus femoris muscles earlier in the dual task (M = 107.43°, SEM = 4.15°) compared to single task conditions (M = 114.17°, SEM = 4.12°), while younger adults showed the opposite trend with earlier muscle activations in single task (M = 119.70°, SEM = 4.05°) than dual task conditions (M = 126.00°, SEM = 4.10°).

However, none of these comparisons were significantly different from each other (*p*s > .209). There were main effects of LIMB, $F(1, 22) = 18.52$, $p < .001$, $\eta p^2 = 0.46$, and FREQUENCY, $F(1.92, 42.14) = 23.33$, $p < .001$, $\eta p^2 = 0.51$, and interactions of GROUP x LIMB, $F(1, 22) = 9.68$, $p < .001$, $\eta p^2 = 0.31$, and GROUP x FREQUENCY, $F(1.92, 42.14) = 3.65$, $p = .017$, $\eta p^2 = 0.14$, and LIMB x FREQUENCY, $F(2.59, 56.95) = 9.50$, $p < .001$, $\eta p^2 = 0.30$. These main effects and interactions were most effectively interpreted in the significant interaction of GROUP x LIMB x FREQUENCY, $F(2.59, 56.95) = 3.34$, $p = .024$, $\eta p^2 = 0.13$. As mentioned in 3.2.4, the value 180° indicated that the muscle burst occurred approximately at the time of movement onset in the corresponding limb. Similarly, a value less than 180° indicated that muscle burst occurred prior to the time of movement onset, while values more than 180° indicate that muscle burst occurred later than the time of movement onset. As can be seen in Figure 3.8, young adults showed a development of phase advances of EMG onset relative to movement onset with increasing movement frequency. Older adults, in contrast, did not significantly change the phase relation between EMG and movement onset from 60 % to 100 % of CF

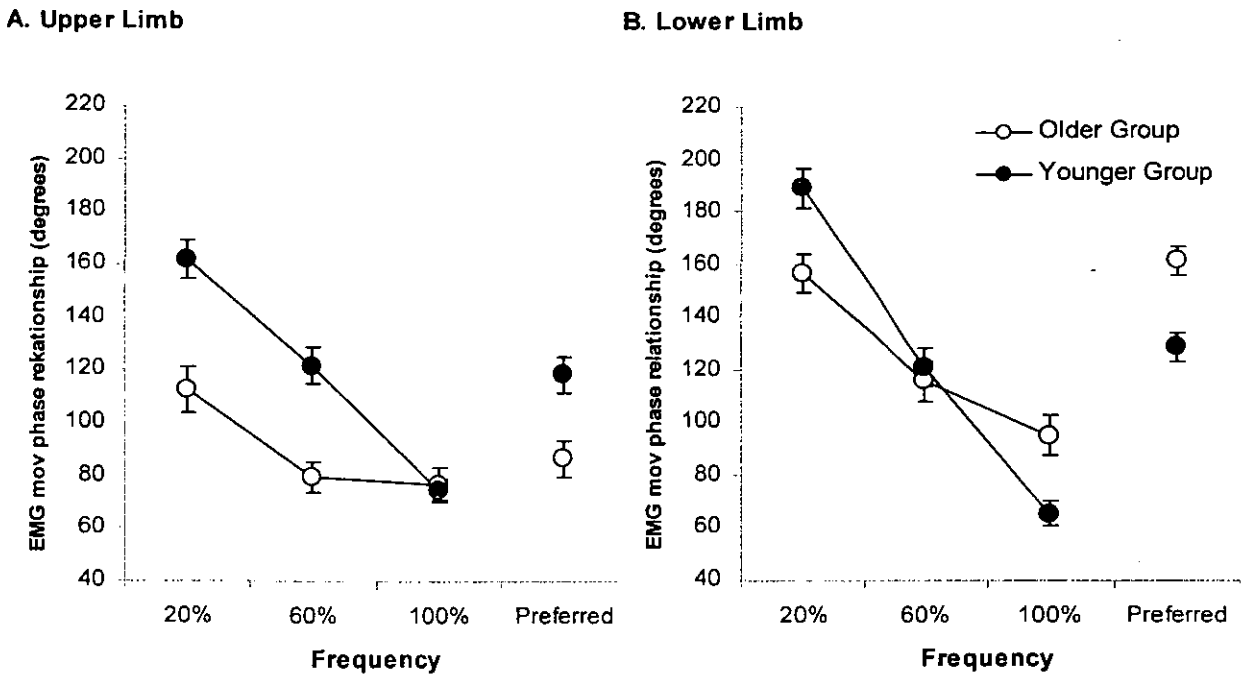


Figure 3.8 EMG and movement phase relationships in A. Upper limb and B. Lower limb for younger and older adults across different movement frequencies.

EMG phase relationship. To investigate the relationship between the timing of muscle recruitment in two limbs, the EMG phase relationship between biceps brachii and rectus femoris was examined using a 2 x 2 x 2 x 4 (GROUP x TASK x LIMB COMBINATION x FREQUENCY) ANOVA. The main effects of GROUP, F (1, 22) = 13.28, p = .001, ηp^2= 0.38, LIMB COMBINATION , F (1, 22) = 6.65, p = .017, ηp^2= 0.83, and FREQUENCY, F (3, 66) = 18.50, p < .001, ηp^2= 0.46, were both significant, with these main effects were most effectively interpreted by the significant interactions of GROUP x LIMB COMBINATION , F (1, 22) = 7.45, p = .012, ηp^2= 0.25, and GROUP x FREQUENCY, F

(3, 66) = 4.45, p = .007, ηp^2= 0.17. As can be seen in Figure 3.9, the interaction of GROUP x LIMB COMBINATION showed that the two muscles were activated with different timing by older adults in the ipsilateral and contralateral limb combination; specifically, older adults exhibited upper limb muscle bursts which were more advanced (with respect to the lower limb muscle bursts) in the ipsilateral limb combination compared to the contralateral limb. In contrast, the younger group exhibited muscle bursts which were anti-phase, i.e., -180° out of phase for both ipsilateral and contralateral limb combinations. The group difference in upper limb muscle activation was significant in the ipsilateral limb combination ($p < .05$), but not in the contralateral limb combination.

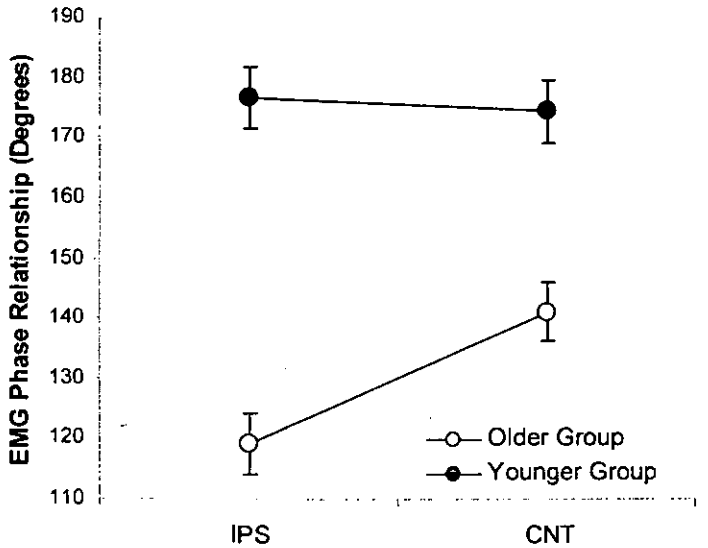


Figure 3.9 EMG phase relationship between biceps brachii and rectus femoris for younger and older adults across limb combinations. IPS: Ipsilateral limb combination, CNT: Contralateral limb combination. *Note:* EMG phase relationship value 180° indicates simultaneous activation of biceps brachii and rectus femoris. Value more than 180° indicates rectus femoris activation advance relative to biceps brachii, while value less than 180° indicates advanced biceps brachii bursts.

A similar analysis of the GROUP x FREQUENCY interaction revealed that the older adults activated the biceps brachii muscle prior to the rectus femoris at all frequencies. Furthermore, for these older adults the upper limb muscle burst was more advanced in the 20 % of CF than 100 % of CF ($p < .01$) (Figure 3.10). In contrast, for the younger adults the 20 % of CF condition differed significantly from the other frequency conditions: in the preferred frequency condition muscle bursts occurred in almost perfect anti-phase, while there was tendency to activate the lower limb prior to the upper limb in the 60 % and 100 %

of CF conditions. At the slowest frequency the upper limb was activated prior to the lower limb muscle in a similar pattern to that exhibited by older adults. In contrast, older adults activated the biceps brachii muscle prior to the rectus femoris at all frequencies.

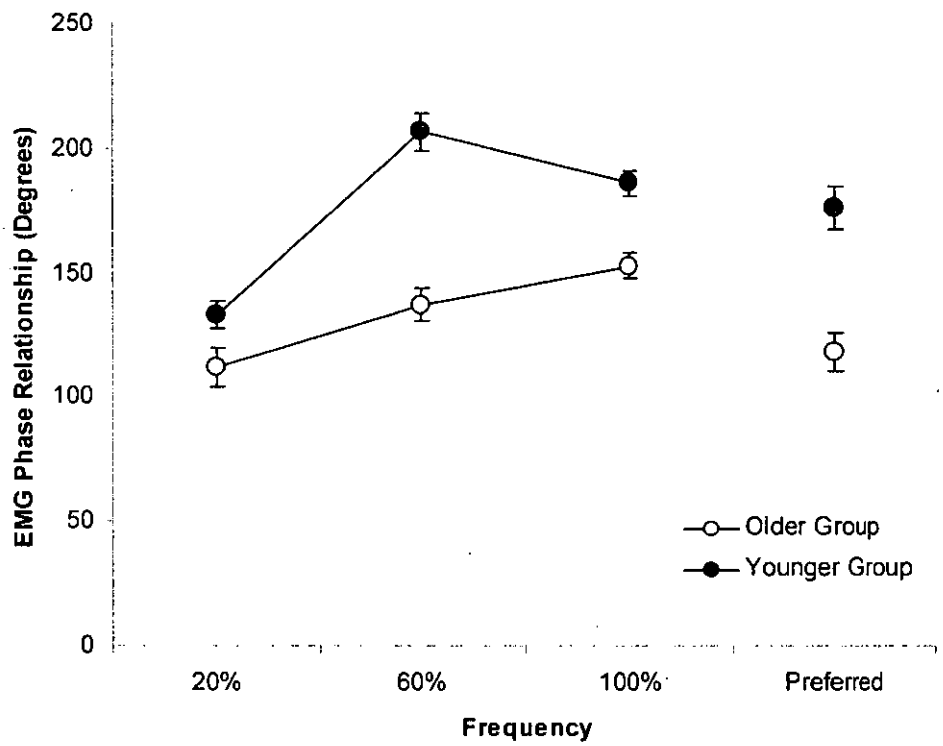


Figure 3.10 EMG phase relationship between biceps brachii and rectus femoris for younger and older adults across movement frequencies.

3.4 Discussion

The present study examined age-related changes in the production of non-isodirectional movements performed with either ipsilateral or contralateral limb limbs. Of particular interest, was the relationship between aging and the central cost associated with interlimb

coordination. With regard to age-related changes there were four main findings. First, older adults had lower critical and preferred frequencies than younger adults. Second, despite moving slower than younger adults, older adults exhibited less accurate and less stable coordination performance than younger adults at 100 % of CF. Third, EMG recordings showed differences in the timing of muscle activation between younger and older adults. Finally, the coordination of arm and leg movements in older adults required greater attentional costs than in younger adults.

Age-related differences in interlimb coordination

Although statistically not significant, the predetermined critical frequency (CF) exhibited by the older adults was lower than the younger adults. Both groups of participants, however, were unable to maintain the required frequency during the 100 % of CF experimental trials with the frequency produced by older adults being significantly lower than that of younger adults. This suggests that both groups slowed down in the experimental sessions to avoid a spontaneous transition from non-isodirectional to isodirectional coordination. The larger reduction in movement speed in older adults may be linked to their preference of accuracy rather than speed (Goggin & Stelmach, 1990). This

tendency to sacrifice speed for accuracy was more evident in older than younger adults and has been reported in other studies of interlimb coordination (Serrien et al., 2000; Wishart et al., 2000).

The lower critical and preferred frequencies exhibited by older adults are consistent with the suggested general motor slowing with age (Hunter et al., 2001; Morgan et al., 1994). Older adults also showed a significantly greater deviation from target frequency and increased cycle duration variability in the 20 % of CF trials in comparison to the younger adults. The difficulty evident in the older group in accurately producing movements much slower or faster than their preferred speed suggests that the ability to control movement timing decreases with age (Krampe, 2002).

Although task difficulty was equated for the two groups, there were group main effects for both AE and SD of relative phase. Overall, older adults showed greater error in maintaining the required relative phase and less stable coordination than younger adults. The difference in the stability of the coordination patterns between the two groups was most noticeable at 100 % of CF when participants were also required to perform a visual reaction time task at the same time. It has been argued that as the quality of afferent information from the limbs declines with age older adults must monitor sensory feedback

more carefully during a coordination task (Seidler & Stelmach, 1995). Thus while older adults were able to produce comparable performance to younger adults under single-task conditions, when attention had to be divided between the coordination and probe RT tasks the older group were unable to maintain comparable pattern stability in the most difficult condition (i.e., 100 % of CF). However, it should be noted that age differences in attentional cost was constant across conditions. If older adults needed greater attentional resources to perform the coordination task at 100 % of CF than RT would be expected to be longer in this condition than at the lower movement frequencies. One possible explanation of the lack of RT delay in the 100 % of CF is that older adults prioritized RT task despite instructions to prioritize the coordination tasks.

The observed age difference in coordination task performance contrast with Heuninckx et al. (2004) who found that when task difficulty was equated between younger and older adults age-related differences disappeared. In that study, however, task difficulty was equated by comparing the performance of older adults at 1 Hz with that of younger adults at 1.5 Hz. In the present study task difficulty was determined for each individual participant based on their predetermined critical frequency. The existence of age-related differences under precise task equalization procedures provides strong evidence that the ability to

coordinate arm and leg movements is adversely affected by the aging process.

Age-related changes in neuromuscular control

The analysis of the phase relationships between muscle activation patterns and the ensuing related limb movement indicated an increase in the phase lead of the muscle burst relative to the limb movement with increasing movement frequency in younger adults. This strategy may have been used to decelerate limb movements and promptly shift to the next phase. The phase advance of the rectus femoris burst, for example, at higher frequencies was necessary to allow a quick transition from the flexion to extension phases of the cyclical movements. This result supported the findings of study by Baldissera, Borroni, and Cavallari (2000) in which an increasing phase advance of extensor carpi radialis (ECR) hand muscle (with respect to hand movement) and tibialis anterior (TA) foot muscle (with respect to foot movement) were observed during non-isodirectional coordination of hand and foot. In contrast to the young adults in the current study, our older group showed a similar phase relationship between both the arm and leg muscles and the respective limb movements at 60 % and 100 % of CF. At 100 % of CF, participants were required to produce bursts of muscle activity rapidly in order to move their limbs at the desired rate.

Regulation of muscle activation has been shown to degrade with advancing age (see review, Barry & Carson, 2004), and this reduced temporal control of muscle bursts at higher frequencies is possibly the cause of the lack of phase modulation from 60 % to 100 % of CF in older adults. In order to investigate this possibility, EMG activities from the anotagonist muscles should be recorded in future research. The EMG data from agonist and anotagnist muscles may provide useful information regarding phasic component of muscle activities.

With regard to phase coupling at the neuromuscular level, the EMG phase relationship measure showed that older adults activated biceps brachii earlier than rectus femoris (across all movement frequencies), while the young participants activated rectus femoris earlier than biceps brachii in the 60 and 100 % of CF conditions, i. e., the young adults increased the EMG phase difference between the rectus femoris and biceps brachii in response to increased movement frequency. In general, to maintain the non-isodirectional coordination mode at the different movement frequencies, the timing of muscle activation in the two segments, having different mechanical properties, was achieved by changing the timing of the muscle bursting as frequency increased (Baldissera et al., 2000). Baldissera and colleagues (2000) found that large movement amplitudes delayed the development of

the phase lag between EMG and limb kinematics. That is, the consistent EMG phase relationship between biceps brachii and rectus femoris in older adults may be due to the lack of modulation of movement amplitude in the leg as a response to frequency increment. As analyses of the phase relationships between muscle activation patterns and related limb movement onsets indicated that at the faster movement frequencies (60-100 % of CF), the rectus femoris bursts in young adults possibly contributed to stopping leg flexion, thereby facilitating change to the extension phase of the cyclical movement. In contrast, older adults appeared to activate the rectus femoris to extend their legs to maintain a pendulum-like motion. The activation pattern evident in young adults may have resulted in the reduced movement amplitude as a function of movement frequency, whereas older adults did not modulate movement amplitude possibly because they opted to swing their legs in a pendulum-like motion and not actively modulating movement amplitude at the fast movement frequencies. It is possible that differences in muscular strength contributed to the different strategies adopted by the two groups. That is, with aging the loss of lower limb strength exceeds the loss of the upper limb strength (Frontera et al., 2000; Lynch et al., 1999). The strategy adopted by the older adults in this study may reflect reduced lower limb control in that group. It is also possible that allowing the leg to swing in an automatic

pendulum-like motion reduced for older adults the attentional demands of actively coordinating arm and leg movements with the pacing metronome.

Attention and interlimb coordination

A major aim of the present study was to examine the relationship between aging, attention and interlimb coordination in the light of equivocal findings from previous research. Mean probe RT was significantly slower in older adults than in the younger group. The lack of any significant interactions involving group indicated that the slower RT in the older group was evident across all single- and dual-task conditions (see Figure 3.8). While increases in the conduction time of auditory and kinesthetic information through neuronal loss and demyelination have been linked to increased RT with aging, recent EEG studies suggest that increased motor-response generation processes may be the primary cause of motor slowing in the aged (Falkenstein, Yordanova, & Kolev, 2006; Roggeveen, Prime, & Ward, 2007; Yordanova, Kolev, Hohnsbein, & Falkenstein, 2004). That is, older adults require a greater and longer activation of the contralateral motor cortex than younger adults to produce a motor action (Falkenstein et al., 2006).

A striking and somewhat unexpected feature of the RT data shown in Figure 3.8 is the

similarity in the pattern of RTs across limb combination and frequencies for both age groups. Although the older group did demonstrate a greater proportional increase in probe RT than the younger group in the dual-task situation compared to the single RT task situation, these differences were not significant. These results seem to argue against the view that aging effects reflect a decreased pool of attentional resources with age. Rather than a decrease in attentional resources per se, older adults may have paid more attention to the coordination task in order to compensate for decreased visual and proprioceptive capabilities.

For both younger and older participants RT was slowest when the coordination task was performed at the slowest movement frequency (20 % of CF). Interestingly, the coordination pattern was performed most accurately (AE of relative phase) and with greater stability (SD of relative phase) at the 20 % of CF frequency than at 60 and 100 % of CF. This finding appears at odds with previous research showing that attention demands, as measured by probe RT, and pattern stability covary (e.g., Monno et al., 2000). However, one performance measure, cycle duration variability, was elevated at 20 % of CF suggesting that moving the limbs at such a slow rate and synchronising with the external metronome was a difficult and attention demanding task for younger and particularly older adults.

There is some kinematic evidence to suggest that when continuous cyclic arm movements are performed at a sufficiently slow rate they appear to be produced as a series of discrete movements (Nagasaki, 1991). Furthermore, Summers and colleagues (Summers, Maeder, Hiraga, & Alexander, 2008) have shown recently that discontinuous movements require greater attentional resources to produce than continuous cyclical movements. Therefore, it is possible that greater attentional resources were required to coordinate the limbs at the slower rate since these slow movements were produced as a series of discrete movements.

Consistent with previous studies, non-isodirectional patterns involving coordination of ipsilateral limbs were more variable in terms of cycle duration and relative phase measures and more attention demanding than patterns involving coordination of contralateral limbs (Hiraga et al., 2004, 2005; Meesen et al., 2006). Somewhat surprising, however, was the finding that probe RT during performance of the coordination patterns at 100 % of CF did not differ from that obtained during performance at 60 % of CF and at the individual's preferred speed. One likely explanation for this result is the observation that both groups of participants had difficulty in accurately producing the coordination patterns at the required 100 % of CF. This was particularly the case for the older adults evidencing a high proportion of trials that did not meet the criteria for inclusion in data analysis. As a

consequence the older adults, and to a lesser extent the younger group, produced the patterns at a frequency considerably slower and possibly less attention demanding than the required frequency. Furthermore, the similarity between probe RTs during unpaced preferred frequency trials and metronome paced trials at 60 and 100 % of CF suggests that the requirement to synchronize arm and leg movements with a metronome was not the source of increased probe RT during dual-task trials.

It is interesting to speculate whether the increased vocal response time to probe stimuli during dual-task trials was due to the attentional cost of coordinating an arm and leg or whether some form of structural interference was operating between the interlimb coordination task and movements of the vocal apparatus. There is strong evidence of interactions between vocal and manual movements (see Peters, 1990; Summers, 1990 for review). A number of recent studies using transcranial magnetic stimulation (TMS) have also demonstrated that the excitability of corticospinal projections from the primary motor cortex to a target muscle can be influenced not only by voluntary contractions of that muscle but also by contractions of other (remote) muscles not directly involved in the primary motor action (e.g., Sohn, Jung, Kaelin-Lang, & Hallett, 2003; Tazoe, Endoh, Nakajima, Sakamoto, & Komiyama, 2007). At a behavioural level, simple unimanual

reaction time has been shown to be delayed when rhythmic oscillatory movements were simultaneously performed with the opposite hand compared to when the contralateral hand remained quiescent (Begeman, Kumru, Leenders, & Valls-Sole, 2007). The authors suggest that inhibition of contralateral motor pathways during the attention-demanding movement task may have contributed to slowing of the RT task. It is possible that a similar inhibitory mechanism was operating in the present study causing a delay in vocal RT during concurrent cyclical movements of the hand and foot. Furthermore, the significantly longer probe RT during the coordination of the right hand and right foot (ipsilateral) compared to the right hand and left foot (contralateral) could be related to degree of neural crosstalk between the cortical representations of the muscles engaged in the coordination and probe RT task. Kinsbourne and Hicks (1978) hypothesized that functions that are primarily subserved by the same hemisphere are closer in functional cerebral space than functions that are primarily subserved by different hemispheres. In the present study in the dual-task situation involving coordination of ipsilateral limbs, movements of the hand, leg and vocal apparatus were controlled by the same (left) hemisphere, whereas when contralateral limbs were involved only the right hand and voice shared the same hemisphere. Whether interactions between areas within the motor cortex underlie the difference in probe RT

between the ipsilateral and contralateral limb combinations is the subject of the third study in the present research.

In conclusion, across all dual-task conditions responses to secondary task probe stimuli were longer in older adults than their younger counterparts. If, as traditionally assumed, probe RT indexes the amount of attention allocated to the primary task, then the amount of additional attentional effort exerted by older adults remained constant across conditions. However, this does not necessarily mean that attention plays little role in the explanation of age-related decline in the performance of interlimb coordination. A profound age difference was emerged in the most demanding 100 % of CF condition, particularly attentional task was performed concurrently. This is possibly due to the strategy adopted by older adults allowing the leg to swing in an automatic pendulum-like motion at higher movement frequency rather than coordinating their limbs. The larger movement amplitudes and unchanged timing of lower leg muscle (rectus femoris) activation relative to the limb movement in older adults compared to younger adults also support this view. This strategy may have contributed to reserve the amount of additional age-related attentional effort in constant levels across conditions by reducing the amount of attention allocated to the motor task at the higher movement frequencies. Hence, the results of present study seemed to

suggest that the effects of aging on motor behaviour are exaggerated during complex motor tasks requiring increased involvement of attentional function.

Chapter 4 Literature Review (Part 2)

Age-Related Differences in the Central Cost of Interlimb Coordination

The empirical study in Part 1 of the research examined the age-related changes in interlimb coordination performance and attentional cost when task difficulty was standardized by adjusting movement speeds at an individual level. A dual-task paradigm was employed in which probe RT was used to index the amount of attentional cost required to perform the primary interlimb coordination task. In general, older adults demonstrated slower movement speed and less stable coordination performance compared to younger adults. Age differences were particularly evident in the most demanding condition (non-isodirectional coordination pattern with ipsilateral limbs). Although reaction times were longer in older adults, the age difference was constant across conditions involving different levels of task difficulty. The results suggest that attentional deficits were not the main cause of the declined coordination performance in older adults. However, the possibility that older adults sacrificed the coordination task for the RT task cannot be excluded, even though participants were instructed to prioritize the motor task. The dissociation between the measure of attentional cost and coordination pattern stability evident in Experiment 1 also indicates a need to further evaluate the role of central attentional resources in the control of interlimb coordination. As mentioned in Chapter 2.2, in divided attention tasks

performance can be influenced by the similarity of processing and the input-output modalities of the two tasks. It is possible, therefore, that the increased vocal response time to probe stimuli during dual-task trials may to some extent reflect structural interference. There is strong evidence of interference between vocal and manual movements (see Peters, 1990; Summers, 1990 for review). In Experiment 2 the relationship between interlimb coordination and attentional resources in younger and older adults was investigated using EEG to provide a direct measure of the CNS activity associated with mental resource allocation. Importantly, the P300 component of the event-related potential (ERP) has been shown to be independent of the processes of motor preparation and execution (Kok, 1997). The P300 component of the ERP, therefore, can be used to assess central information processing in older adults during interlimb coordination unconfounded by possible structural interference. In terms of the neurophysiological mechanisms underlying age-related changes in interlimb coordination, a number of studies have used neuroimaging technology to identify particular areas of the brain that are involved in interlimb coordination (e.g., Heuninckx et al., 2005; 2008), though the precise nature of the mechanisms remains unclear. It was therefore of particular interest to examine age-related

differences in neurophysiological indices during interlimb coordination in Part 2 of the study.

4.1 Age-Related Changes of Cortical Activation and Cognitive Function

Until recently, brain volume reduction with age was believed to be a consequence of neuronal loss (Kemper, 1994). However, it is now believed that the reduction of total neuronal number is insignificant as a cause of atrophy. Rather, current theories consider the contribution of cell shrinkage, dendritic regression, and a reduced synaptic density to gross brain volume reduction (Uylings, West, Coleman, De Brabander, & Flood, 2000). However, the functional influence of these neuronal changes on cognitive function is unclear (Tisserand & Jolles, 2003). Nonetheless, it seems that age-related changes in cognitive processing are associated, at least partly, with alteration of brain morphology and functioning. In recent years, functional neuroimaging techniques including functional magnetic resonance (fMRI) and positron emission tomography (PET) have provided a link between cerebral and cognitive changes with advancing age.

Using these neuroimaging techniques, age-related differences in the pattern of brain activation have been demonstrated not only during cognitive tasks (D'Esposito, Zarahn,

Aguirre, & Rypma, 1999; Esposito, Kirkby, Van Horn, Ellmore, & Berman, 1999; Grady, 2000; Townsend, Adamo, & Haist, 2006), but also during motor tasks (Calautti, Serrati, & Baron, 2001; Heuninckx et al., 2005; Hutchinson et al., 2002; Mattay et al., 2002; Sailer, Dichgans, & Gerloff, 2000; Ward & Frackowiak, 2003; Wu & Hallett, 2005). These studies indicate that older adults recruit more areas of the brain than younger adults and/or elicit higher activation in brain areas associated with the task. The most common explanation for the additional activation in older adults is the operation of a compensatory mechanism, which involves reorganization and redistribution of functional networks to adjust for structural and neurochemical changes with advancing age (Mattay et al., 2002; Sailer et al., 2000). Using PET during a memory task, Cabeza and colleagues found that high-performing older adults engaged the prefrontal cortex (PFC) bilaterally, while low-performing older adults showed lateralized PFC activity (Cabeza et al., 2002). Cabeza (2002) proposed the Hemispheric Asymmetry Reduction in Old adults (HAROLD) model in which bilateral activation of PFC region is seen as beneficial since it involves the recruitment of an alternative network. The reduced asymmetrical brain activity in older adults is not exclusively in the PFC, but also commonly found in parietal regions (Cabeza, 2004; Lee et al., 2006). The model has been supported by findings in a variety of cognitive

tasks, including episodic memory retrieval (Cabeza et al., 1997; Grady, Bernstein, Beig, & Siegenthaler, 2002; Madden, Gottlob, & Allen, 1999), working memory (Dixit, Gerton, Dohn, Meyer-Lindenberger, & Berman, 2000; Reuter-Lorenz et al., 2000), perception (Grady et al., 1994; Grady, McIntosh, Horwitz, & Rapoport, 2000), and inhibitory control (Nielson et al., 2002). Although there are a few studies examining cognitive task performance which do not entirely agree with the functional compensation notion (Colcombe, Kramer, Erickson, & Scalf, 2005; Langenecker & Nielson, 2003; Nielson et al., 2002), for motor tasks the additional activation of brain areas appears to be associated with better task performance. For example, Wu and Hallett (2005) examined the effect of aging on automatic motor performance using fMRI. Participants practiced complex sequential finger movements until they could perform the task automatically. While achieving similar performance level as younger adults, older adults exhibited greater activity in the cerebellum, premotor area, parietal cortex, contralateral prefrontal cortex, anterior cingulate, caudate nucleus and thalamus, and supplementary motor area. The increased activation in task related brain areas in older adults is in line with the findings of Heuninckx and colleagues (2005) who employed an interlimb coordination task involving the coordination of upper- and lower-limbs in isodirectional and non-isodirectional

coordination patterns. An important finding was that in the non-isodirectional coordination mode, additional activation of areas in the frontal lobe associated with cognitive processing was found in addition to the dorsal premotor area, posterior parietal cortex, and cerebellum which have been shown previously to be involved in interlimb coordination tasks (Debaere et al., 2001; Ehrsson, Kuhtz-Buschbeck, & Forssberg, 2002; Sadato, Yonekura, Waki, Yamada, & Ishii, 1997). These findings are consistent with the view that the extra activation of brain areas, especially the frontal lobe, provide a compensatory function in the aged brain to perform motor tasks (Heuninckx et al., 2008).

Electroencephalography (EEG) studies have also found additional activation in older adults similar to neuroimaging studies. For example, Sailer et al. (2000) found high cortical activity in the contralateral premotor and sensorimotor areas during repetitive finger movements in a younger group, whereas additional activation in the ipsilateral sensorimotor and supplementary motor area was observed in older adults. More diffuse brain activity in older adults is also in agreement with findings from studies using Event Related Potentials (ERPs) (see review, Kok, 2000). A posterior to anterior shift in cortical activity with age has been observed in a number of studies (e.g., Friedman, Kazmerski, & Fabiani, 1997; Pfefferbaum, 1984; Vesco, Bone, Ryan, & Polich, 1993). Furthermore, since

increased frontal activity during cognitive tasks has been demonstrated for older adults by neuroimaging techniques (e.g., Madden et al., 1996; Madden, Turkington et al., 1999; Madden, Turkington, Provenzale, Hawk, & Hoffman, 1997; Mattay et al., 2002), it has been argued that automatic information processing decreases with age requiring older adults to employ cognitive control to perform tasks (Alain, McDonald, Ostroff, & Schneider, 2004; Heuninckx et al., 2005; Heuninckx et al., 2008).

Cognitive tasks have been primarily used in neurophysiological studies reporting extra activation in the aging brain. In contrast, only a limited number of studies (e.g., Heuninckx et al., 2005; Heuninckx et al., 2008; Wu & Hallett, 2005; Yordanova et al., 2004) have investigated age-related changes in human brain activation during motor task performance (Sailer et al., 2000). In addition, the influence of functional changes in the aging brain on the operation of attentional processes is not well understood. Therefore, the specific aim of Part 2 of the research was to investigate age-related changes in attentional processing needed to perform interlimb coordination tasks. A popular application of electrophysiological techniques to study age-related changes in attentional processes has been the use of Event Related Potentials (ERPs), more specifically the P300 component of the ERPs (Polich, 1996).

4.2 Event-Related Potentials (ERPs)

ERPs are obtained from ongoing Electroencephalography (EEG) activity by filtering and averaging the voltage fluctuations that are time-locked to specific stimuli with temporal resolution in the order of milliseconds (Donchin, 1981; Empson, 1986; Fabiani, 2000). The ERP waveform consists of a series of components that refer to latency and polarity, and their stable time relationships to experimental manipulations enable researchers to associate a particular component to task specific processing (Fabiani, 2000; Friedmann, Cycowitz, & Gaeta, 2001). ERPs are measured in terms of the polarity of peak amplitude (either positive or negative) and the latency of the cortical waveform. According to Coles and colleagues (Coles, Gratton, & Fabiani, 1990), the ERP is the manifestation of brain activities that are elicited in preparation or in response to discrete events. In other words, ERPs reflect cortical activation to a specific stimulus in a time-locked manner. The ERP waveform is a reflection of synchronistic activation of a large population of neurons from both cortical and subcortical regions. Although spatial resolution of ERPs is limited, since multiple neural generators are likely to be involved in the activation in the brain (Fabiani, 2000) multichannel recordings provide an estimation of the intracerebral locations of the cerebral

processes (Picton et al., 2000). Furthermore, distortion of the electric field caused by the skull produces another difficulty in identifying the source of an ERP component without application of dense electrode arrays and dipole analysis, or sophisticated imaging technologies including fMRI or PET (Fabiani, 2000). Contrary to the limited spatial resolution, ERPs have an advantage in temporal resolution that is in the order of milliseconds, thus enabling ERPs to accurately measure the timing of information processing activity in the human brain (Picton et al., 2000).

Empson (1986) suggested that the first 80ms of the ERP is influenced by the physical properties of the stimulus and is primarily modality specific. These waveforms include components consisting of a continuum between exogenous and endogenous potentials (Picton et al., 2000). The exogenous potentials have components which are modulated by the physical properties of the stimulus while the endogenous potentials are manifestations of information processing such as stimulus evaluation (Empson, 1986; Fabiani, 2000; Picton et al., 2000). In addition, ERP components evoked after 100 ms post stimulus onset are sensitive to both physical and psychological properties of the eliciting stimulus and are known as mesogenous (Fabiani, 2000).

The utilization of ERPs to examine age-related changes in attentional processes is beneficial because (1) the components of ERPs enable us to identify the mechanisms that are relevant to the selection of information that may show age-related changes, and (2) the late components of the ERP, such as P3, are believed to have an association with attentional functions that specifically index the capacity of attention (Kok, 1997).

P3b component

P3 is a positive deflection that is generally elicited between 300-600ms after stimulus presentation (Figure 4.1). P3 is further separated into P3a and P3b components. P3a is usually observed following the presentation of infrequent and novel stimuli while P3b can be observed in response to target stimuli (Squires, Squires, & Hillyard, 1975). P3a reflects the shift of involuntary attention to changes in the environment and has a frontal-central distribution. In contrast, P3b generally shows a posterior-parietal distribution and is regarded as an index of the allocation of central resources (Kramer & Spinks, 1991; Parasuraman, 1990). It seems that P3b latency reflects the timing of mental processing and has been found to be shorter in automatic processing conditions (Hoffman, Simons, & Houck, 1983; Kramer & Spinks, 1991). It has also been reported that shorter P3b latency is associated with better performance (Key, Dove, & Maguire, 2005). Therefore, P3b latency

is regarded as an index of information processing speed independent of sensorimotor and motor processing stages (Coles, 1995; Kok, 2001).

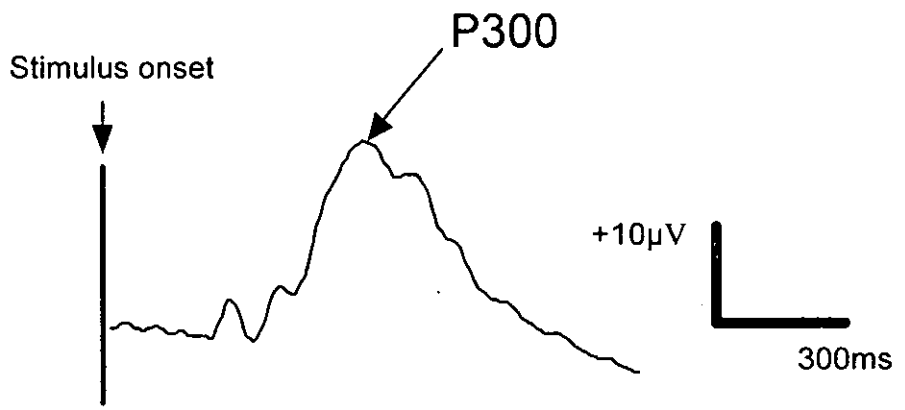


Figure 4.1 Schematic illustration of the ERP waveform and P300 component.

It has been suggested that there is a close association between P3b amplitude and the intensity of processing (Kok, 1990; Polich & Kok, 1995), especially perceptual/central processing rather than response-related processing (Kok, 2001). Kok (2001) suggested that P3b amplitude proportionally decreases with processing demands if the task is perceptual-centrally demanding while P3b is intact if the task demands response-related resources. In this way, the P3b is regarded as the index of the utilization of resources for information processing. Therefore P3b amplitude is interpreted as an index of utilization of a central resource, whereby its amplitude correlates inversely with task difficulty (Donchin, Miller, & Farwell, 1986; Fjell & Walhovd, 2001). Based on these interpretations of P3b the

available attentional resources for a task have been intensively investigated using a dual-task paradigm. The basic idea of the approach is that manipulation of difficulty of the defined primary task is reflected in the modulation of available resources for a concurrently performed secondary task (Kok, 2001). Surprisingly, only a few studies have incorporated groups of older adults in investigations of attentional resource in the dual-task paradigm (Kok, 2000).

4.3 Age-related Changes in P3b Component of the ERPs

The P3b component of ERPs has been utilized to study the effect of aging on neural activity, mainly focusing on attentional and memory processes (Polich, 1996). It is beneficial to use the P3b component for an aging study since P3b provides a 'pure' measure of CNS activity associated with attentional resource allocation that is independent from the response selection process (Magliero, Bashore, Coles, & Donchin, 1984; Polich, 1987) and is not influenced by confounding peripheral response factors (Dywan, Segalowitz, & Unsal, 1992). P3b is most frequently studied using an oddball task, which presents two types of stimuli in a random order, a common and a target stimulus. The participant is required to respond to the target stimuli by pressing a button or mentally counting target stimuli (Kok,

1997). A consistent finding is a significant increase of P3b latency and a smaller amplitude of the P3b to target stimuli in older adults in comparison to younger subjects (Amenedo & Diaz, 1998; Czigler, Csibra, & Csontos, 1992; Donchin et al., 1986; Dujardin, Derambure, Bourriez, Jacquesson, & Guieu, 1993; Iragui, Kutas, Mitchiner, & Hillyard, 1993; Smith, Michalewsky, Brent, & Thompson, 1980). These studies employed an auditory oddball task, but similar results have been reported using visual oddball tasks (Amenedo & Diaz, 1998; Czigler et al., 1992; Donchin et al., 1986; Dujardin et al., 1993; Looren de Jong, Kok, & van Rooy, 1989; Pfefferbaum, 1988).

Another distinct pattern of age-related changes in P3b is more diffuse brain activity in older adults than younger adults (Kok, 2000). Specifically, older adults show relatively smaller P3b amplitude at parietal sites and a larger amplitude at frontal sites compared to younger adults (Anderer, Semlitsch, & Saletu, 1996; Friedman et al., 1997; Iragui et al., 1993; Pfefferbaum, Ford, Roth, & Kopell, 1980; Pfefferbaum, 1984; Vesco et al., 1993). In summary, the reviewed studies indicate that reduced P3b amplitude reflects the deployment of attentional resources, while prolonged latency is due to the decreased processing speed in the aging brain (Kok, 2000). Therefore, enhanced activity in additional areas in older adults has been regarded as functional compensation in the aging brain (Sailer et al., 2000).

4.4 ERPs and Motor Task Performance

In the past, ERPs in the area of motor control were mainly applied to investigate motor preparation or tasks involving minimal movement since artifacts from movements compromise data acquisition (Janelle, Duley, & Coombes, 2004). For example, Schubert and colleagues (Schubert et al., 1998) aimed to assess attentional demand in a cyclical thumb adduction task with or without force control by examining the P3b component of the ERP. Each motor task was performed concurrently with an auditory classification task. As expected, smaller P3b amplitude to auditory task stimuli was observed in the force control condition compared to without force control condition indicating that the force task required a higher demand on attentional resources. Although movement-related artifacts are a problem for data acquisition when motor tasks are used, some studies have overcome this methodological limitation and have successfully examined the function of attention in motor task performance. For example, Murray and Janelle (2007) investigated the effect of psychological stress in attentional processing using a racecar driving simulation. In the car driving simulation task, participants were required to manipulate a steering wheel, and brake and accelerator foot pedals making intermittent movements of body segments. They

found a reduction of P3 amplitude to a secondary visual signal detection task in competitive sessions, indicating that the stressful environment compromised the amount of allocation of attentional resources. Thus, it was suggested that the application of ERPs during the performance of a motor task provides useful information to understand the role of attention in motor performance.

Recently, the central cost of interlimb coordination was investigated in a dual-task paradigm by Matthews and colleagues (Matthews et al., 2006). As mentioned in Chapter 2.2, there is strong evidence that attentional allocation impacts on the pattern stability of interlimb coordination. This study aimed to provide a direct neurophysiological measure of the central cost associated with stabilizing bimanual coordination patterns using ERPs. Participants performed a bimanual coordination task and a visual oddball task at the same time while prioritizing one of the tasks alternately. When two qualitatively distinct tasks (a primary and secondary task) are performed concurrently, a performance trade-off often appears in the secondary task. Performance trade-off refers to decline of task performance in one task to maintain high level of task performance in the other task. It has been suggested that the performance trade-off reflects the competition for single (Kahneman, 1973) or multiple (Navon & Gopher, 1979; Wickens, 1984, 1989, 2002)

limited resources or processing capacity by the tasks being performed. Thus secondary task performance can be used to assess the extent of residual available resources during performance of the primary task (Wickens, 1984). In the study of Matthews et al. (2006) as expected, performance trade-offs induced by task prioritization were accompanied by variations in P3b amplitude. That is, improved motor performance through prioritizing the motor task induced smaller P3b amplitude to target stimuli in the visual oddball task relative to when the oddball task was prioritized. Matthews and colleagues (2006) concluded that the P3b component of the ERP provides a valid measure of the central attentional cost of interlimb coordination task while minimizing the chance of introducing structural or response-related interference. This study, therefore, indicated the utility of ERPs as a direct measure of CNS activity during an interlimb coordination task.

In investigations of aging effects on motor functions, a number of studies have investigated ERPs accompanying motor preparation utilizing the contingent negative variation (CNV), an index of the state of readiness or expectancy in the CNS (e.g., Dirnberger et al., 2000; Golob, Ovasapyan, & Starr, 2005; Hillman, 2002). CNV is an increasing negative potential shift of EEG signals associated with an anticipated response to an expected stimulus (Rosahl & Knight, 1995). CNV develops during a short (~1-5 s) interval between two task-

relevant stimuli in which the second stimulus requires a motor response. The late component of the CNV is considered to be generated by a network of cortical and subcortical structures, which includes prefrontal, posterior parietal, temporal, premotor, primary motor and somatosensory cortex, and the basal ganglia (Golov et al., 2005). For example, Hillman et al., (2002) measured the CNV of younger and older adults who engaged in a decision making task in which participants were asked to choose the taller of two bars presented on a computer screen. An age difference was found across hemispheres as younger adults demonstrated increased CNV in the left hemisphere compared to right hemisphere. This result was expected since the implemented right-handed task would be expected to elicit the CNV in the contralateral left hemisphere (Brunia & Vingerhoets, 1980), while older adults showed consistent CNV amplitudes across hemispheres. The authors concluded that the similar level of CNV amplitude across hemispheres in older adults indicated increased homogeneity in regional neural activity with aging, whereas younger adults successfully allocated specific motor resources to fulfill the task's demands.

In summary, ERPs are useful in the investigation of central attentional resources during the performance of motor tasks. With the exception of Matthews et al., (2006) study of bimanual coordination, there have been no previous studies investigating the activity in

the CNS during an interlimb coordination involving upper- and lower-limbs using ERPs.

4.5 Summary

Previous studies using a dual-task paradigm have shown that manipulations of primary task difficulty impact on the amplitude of the P3b component of the ERP. More difficult task conditions elicit smaller P3b amplitudes relative to easier conditions. Based on this evidence, it has been argued that P3b indexes the amount of central resource available for the secondary task. In older adults a decreased central resource and increased conscious cognitive control, rather than automatic control, has been suggested by smaller P3b amplitudes and more diffuse brain activity. As reported in chapter 2, reduced attentional resources have been linked to age-related changes in motor coordination (Woollacott & Shumway-Cook, 2002). The P3b component of ERPs can provide useful information with regard to this hypothesis since it allows the investigation of attentional processes during interlimb coordination at a central processing level.

The following chapter (Chapter 5) includes the study which has been submitted to the journal Psychophysiology and is currently under review.

Chapter 5 Experimental Study 2

5.1 Introduction

The results of the first experimental study revealed that in general, older adults showed a similar performance pattern between ipsilateral and contralateral limb combinations, but experienced greater difficulty than younger adults in coordinating non-isodirectional movements using limbs on the same side of the body (ipsilateral). It was also found that coordination performance in older adults declined in the most demanding 100 % of CF condition, particularly when the probe RT task was performed concurrently. These results are in line with previous studies (Heuninckx et al., 2004; Heuninckx et al., 2005) and suggest that the effects of aging on motor behaviour are exaggerated during complex motor tasks requiring increased involvement of cognitive functions, particularly attention (Birren et al., 1980; Spirduso, 1983).

It is possible, however, that the observed age difference on the probe RT task was due to the incompatibility at a structural level between the interlimb coordination task and the probe RT task. That is, the two tasks may share similar structures producing interference which could account for the increased secondary task probe RT during interlimb coordination performance. Heuninckx et al. (2004), using a secondary task that did not

require a motor response, also argued that reduced attentional resources may not be the main cause of the age-related deterioration in ipsilateral, non-isodirectional limb coordination. The authors hypothesized that a reduced ability to process proprioceptive information in the aged may underlie age-related declines in interlimb coordination.

The aim of the second experimental study was to further investigate the relationship between interlimb coordination and attentional processes in younger and older adults using electroencephalography (EEG) to provide a direct measure of the CNS activity associated with mental resource allocation. Specifically, the amplitude of the P300 component of the event-related potential (ERP) has been argued to index the amount of attentional resources allocated during dual-task performance, while P300 latency is thought to reflect the speed of information processing (Kok, 1997, 2001; Polich, 2007). As mentioned in the previous chapter, the P300 component of the ERP appears to be relatively independent of the processes of motor preparation and execution. In the aging literature across a variety of tasks, P300 latency has been shown to increase with age and amplitude usually decreases with a tendency to become more evenly distributed over the scalp (see Linden, 2005 and Polich, 1996, for reviews). The difficulty of the coordination task was manipulated by requiring the performance of the non-isodirectional pattern at two frequencies and with

either ipsilateral or contralateral limbs. In addition, self-determined subjective movement speeds were used to achieve similar task difficulty for young and older adults in the second experimental study. In the first experimental study, standardized movement frequency was used to control the influence of general motor slowing with age. Although the effect of the task difficulty manipulation was reflected in coordination task performance, task difficulty was not reflected in probe RT task performance. That is, more pronounced age-related differences in attentional cost were expected at the highest movement speed (i.e., 100 % of critical frequency) compared to lower frequencies, but this was not the case. This may be due to the fact that older adults performed the coordination task at a slower movement frequency than required at 100 % of CF condition. Of particular interest in the second experimental study was the investigation of age-related changes in central cost during the performance of interlimb coordination. Therefore, it was essential to equate task difficulty between two age groups. For this purpose, subjective self-determined movement speeds were used to achieve similar levels of task difficulty for young and older adults. If the coordination of arm and leg movements requires greater central resources in older adults than younger adults, age-related differences in P3 amplitude would be expected. In turn, if the electrophysiological measures of central cost show no age differences in the presence of

behavioural slowing (RT delay in older adults), it may be possible that the interlimb coordination task and visual RT task share similar structures or mechanisms.

5.2 Method

5.2.1 Participants

There were 32 right-handed volunteers consisting of 16 older adults (8 males, 8 females, mean age 65.5 years, range 60-75 years) and 16 younger adults (8 males, 8 females, mean age 24.31 years, range 19-35 years). Mini-Mental State Examination (Dick, et al., 1984) was used to screen for cognitive deficits in the sample of older adults. The average score of participants in the current study was 29.38 ($SEM = 0.24$). Thus, all participants scored within the normal range (score ≥ 26) and were free of any neurological impairment, symptomatic cardiovascular disease, diabetes and hypertension. Written informed consent was obtained prior to participation in the study. Ethics approval for the study was obtained from the Human Research Ethics (Tasmania) Network.

5.2.2 Apparatus and Tasks

Participants were seated in a custom-made chair identical to that used in the first experimental study (see p. 41). A computer placed approximately one meter in front of the

participant at eye level was used to present visual stimuli for the visual task. EEG data were recorded using a NeuroScan Synamps I system and a Quick-cap with Ag/AgCl electrodes.

Interlimb coordination task

The motor task involved cyclical flexion and extension movements of either contralateral (right arm and left leg) or ipsilateral (right arm and leg) limbs in a 1:1 frequency ratio. The movements were coordinated in a non-isodirectional pattern whereby the limbs moved in opposite directions (i.e., 180° relative phase). The limbs not involved in the coordination task remained at rest. Participants performed the coordination patterns at two movement speeds, preferred (PRF) and fast-as-possible (FAP). The PRF was a movement frequency at which the participant could perform the non-isodirectional pattern for a long period of time, whereas the FAP was the highest frequency at which the participant could accurately maintain the target pattern.

Visual Task

A visual two-stimulus task was used as the secondary task to assess the attentional cost of interlimb coordination. The task involved the presentation of Common (blue circle, 10.18 cm^2) and Target (larger blue circle, 15.20 cm^2) stimuli which were randomly

delivered with probabilities of .80 and .20 respectively. All stimuli were presented for 75 ms with an SOA of 1500ms. The response window was 1000ms. Participants were instructed to respond quickly and accurately to the target stimuli by pressing a response button with their left index finger and to ignore common stimuli.

EEG activity to the visual task stimuli was recorded from three midline (Fz, Cz, Pz) and six homologous scalp positions (F3/4, C3/4, P3/4) according to the International 10-20 system (Jasper, 1958). Electrodes were referenced to linked mastoids and were grounded at AFz with impedances kept below 5 kΩ. EEG activity was recorded with a bandpass filter of 0.15- 100 Hz and digitized continuously at a rate of 1000 Hz. Vertical and horizontal EOG were recorded from electrodes placed above and below the left eye and at the outer canthi of both eyes, respectively.

5.2.3 Procedure

After completing a brief medical questionnaire to ensure inclusion criteria for the study were met and setting up for EEG recording, participants received instructions for both the motor task and visual task. Participants practiced the contralateral and ipsilateral patterns for five minutes with the aid of a Lissajous figure (Figure 5.1) depicting the

angular displacement of one limb against the other in real-time on an x-y plot. Lissajous feedback plots have been shown to be effective in the acquisition of novel coordination patterns by elderly populations (Swinnen, 1998). To assist in determining their self-determined frequency for the FAP trials, participants also performed the non-isodirectional pattern with ipsilateral limbs, synchronizing their movements with an auditory metronome that increased in frequency every seven seconds until they were no longer able to produce the required coordination pattern.

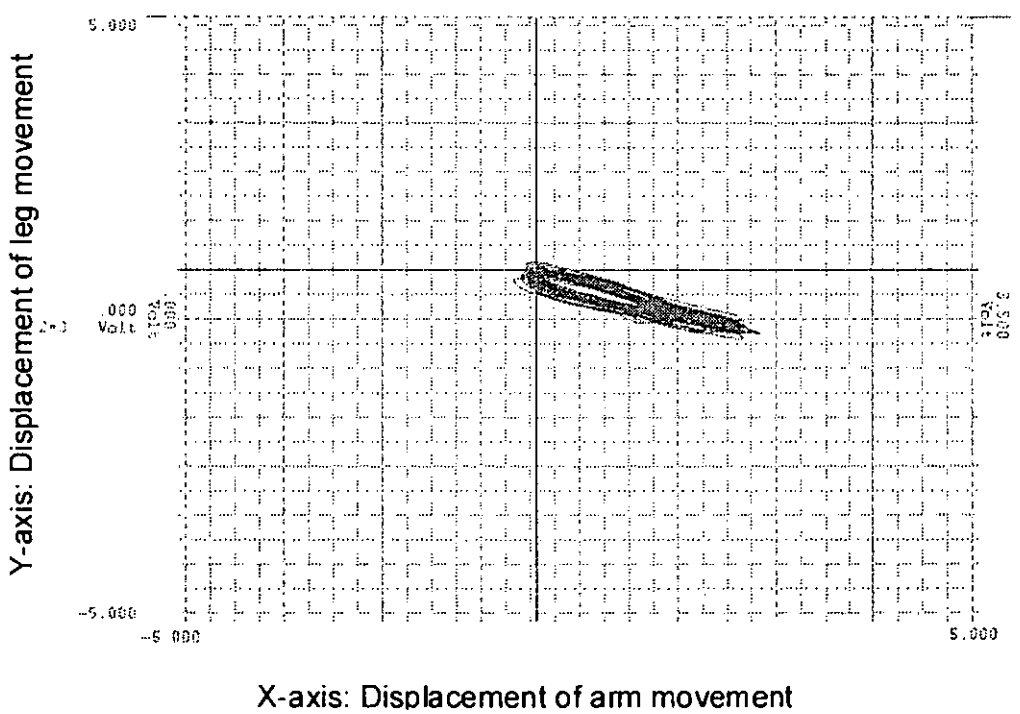


Figure 5.1 A typical illustration of a Lissajous figure

Following the practice sessions for the coordination tasks, participants received instructions and completed a practice trial for the visual task. Instructions were then given

regarding the dual-task conditions involving the concurrent performance of the coordination and visual tasks. A dual-task practice trial was completed at the two movement frequencies using the ipsilateral limb combination. There were a total of 43 experimental trials which were divided into nine blocks. The first and last block consisted of four single coordination task trials: 2 (LIMB COMBINATION) x 2 (FREQUENCY). Each of the middle seven blocks consisted of five trials: one trial involving the single visual task condition and four dual-task trials involving the concurrent performance of the visual task and each coordination task: 2 (LIMB COMBINATION) x 2 (FREQUENCY). Each trial lasted 30 s and the order of conditions was randomized across blocks. Within each dual-task trial 20 visual stimuli were presented, four of which were target stimuli to which participants responded with their left hand. Thus, over the course of the experiment for the single visual task condition and each dual-task condition, responses to 28 visual target stimuli were recorded. Participants were instructed to maintain good performance on the primary coordination task while performing the secondary visual task to the best of their ability.

5.2.4 Data Analysis and Measures

Relative phase measures. Coordination between limb segments was assessed using the same procedure as described for the first experimental study (see p. 45). Absolute Error (AE) of relative phase was obtained as a measure of accuracy of the coordination task, while Standard Deviation (SD) of relative phase provided a measure of pattern stability.

Spatiotemporal measures. The frequency of each cycle (peak-to-peak) was averaged within a trial to obtain mean movement frequency. The variability of movement frequency was assessed using the coefficient of variation to control the influence of absolute differences in standard deviation between conditions, defined as the standard deviation of movement frequency divided by mean movement frequency and presented as a percentage.

Visual task. Behavioural measures were mean reaction times to target stimuli and accuracy (number of correct target detections). Reaction times exceeding the range mean ± 2*SD* in each condition were excluded from data analysis. EEG data were edited using Scan 4.3 software. After merging with behavioural files, continuous EEG files were band-pass flittered at 48dB per octave, with a high band pass of 0.15 Hz and a low pass of 30 Hz. Ocular artifact reduction was performed by regression and artifact averaging (Semlitsch, Anderer, Schuster, & Presslich, 1986). EEG activity was averaged offline for an 1100 ms

epoch commencing 100 ms prior to stimulus onset. High and low voltage cut-offs for artifact rejection were set at 100 μV and −100 μV. Correct responses were baseline corrected at the pre-stimulus interval. ERPs were averaged for common and target stimuli individually for each condition. P3b peak amplitude and latency were determined from grand mean averages and individually derived from within the intervals of 300 ms-600 ms post stimulus.

5.2.5 Statistical Analysis

The data were examined using repeated measures ANOVAs. Huynh-Feldt epsilon corrections were applied where required and Tukey HSD tests were used for post-hoc analyses. Partial η^2 (ηp^2) values were provided as a measure of effect size. An effect size of 0.01 is considered small, 0.06 medium and 0.14 and higher large (Stink & Stroh, 2006).The level of significance for all tests was set at $p < .05$. The spatiotemporal measures of coordination, absolute error of relative phase and SD of relative phase were analyzed using repeated measures ANOVAs with the between subjects factor, GROUP (younger, older), and the within subjects factors, TASK (single, dual), LIMB COMBINATION (ipsilateral, contralateral), and FREQUENCY (PRF, FAP). For analysis of movement frequency, an

additional within-subjects factor, LIMB (arm, leg), was included.

Reaction times in the visual task were analyzed using a repeated measures ANOVA with the between subjects factor, GROUP (younger, older) and the within subjects factors, LIMB COMBINATION (ipsilateral, contralateral) and FREQUENCY (PRF, FAP). Two additional within subjects factors, MIDLINE SITE (frontal, central, parietal) and LATERAL SITE (left, midline, right), were included in the analyses of P3b amplitude and latency. In addition, since the main interest were the dual-task interference effects on ERPs, 2 x 5 repeated measure ANOVAs with GROUP (younger, older) and CONDITION (single visual task, dual ipsilateral PRF, dual ipsilateral FAP, dual contralateral PRF, dual contralateral FAP) as factors were used to analyze P3b amplitude and latency. In all figures error bars are presented as standard error of the mean (SEM). STATISTICA 7.1 software (StatSoft, Inc., OK, USA) was used for statistical analysis.

5.3 Results

As age-related changes in interlimb coordination and the P3b component of ERPs were of primary interest in the present study, all main effects and only interactions involving GROUP as a factor will be reported. Results of all statistical analyses are presented in

Appendix E (in the attached CD).

Behavioural Data: Interlimb coordination tasks

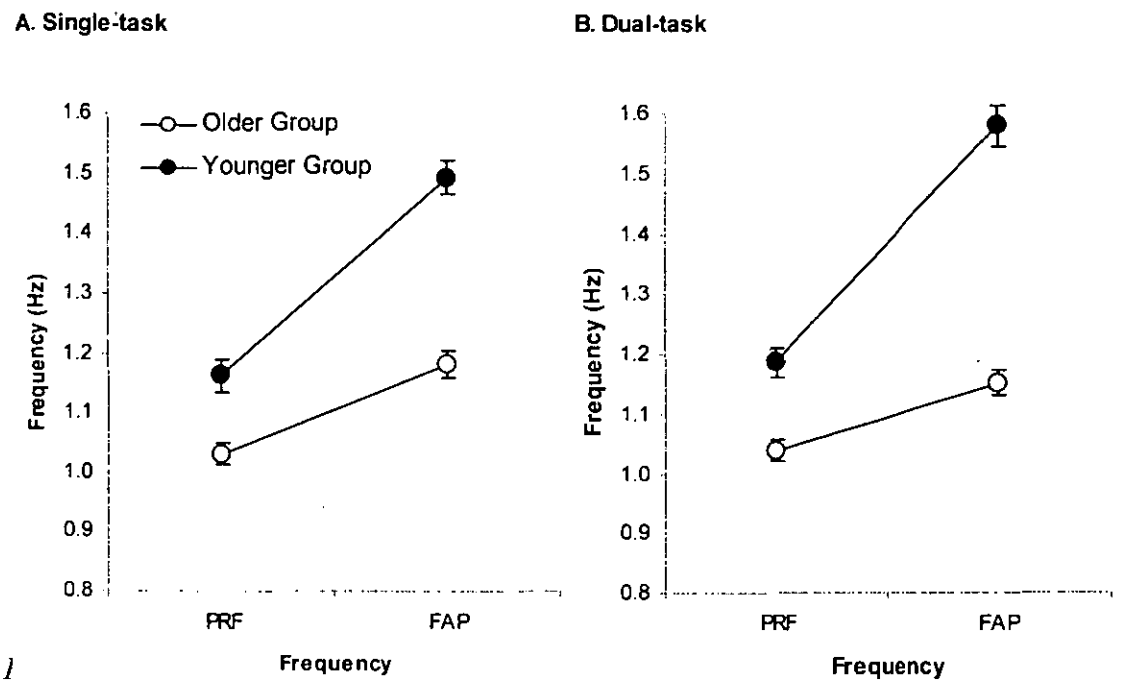
The coordination task data represent the means of trials in which the target relative phase (180°) between the limbs was performed correctly. In line with previous research (Calvin et al. 2004; Heuninckx et al. 2004) a trial was accepted if the absolute error and SD of relative phase were below 70° and 50°, respectively. As would be expected, a greater percentage of trials under the FAP instruction (M = 13.23 %, SEM = 1.83 %) exceeded these values than when participants performed the coordination pattern at their preferred rate (M = 4.69 %, SEM =1.18 %), F (1, 30) = 14.31, p = .001, ηp^2= 0.32. A greater number of trials exceeded the required relative phase value when the coordination pattern involved ipsilateral limbs (M = 11.61 %, SEM =1.66 %) than contralateral limbs (M = 6.31 %, SEM =1.46 %), F (1, 30) = 5.42, p = .027, ηp^2= 0.15. Although older adults (M = 10.99 %, SEM =1.78 %) had more trials discarded than younger adults (M = 6.92 %, SEM =1.33 %), the difference did not reach statistical significance (p = .256).

5.3.1 Kinematic measures

Frequency manipulation. Participants were asked to perform the coordination pattern at

their preferred speed and as-fast-as-possible. Analysis of the frequencies produced by the two groups gave significant main effects of GROUP, $F(1, 30) = 23.21, p < .001, \eta p^2 = 0.44$, FREQUENCY, $F(1, 30) = 36.22, p < .001, \eta p^2 = 0.55$, and their interaction, $F(1, 30) = 7.81, p = .009, \eta p^2 = 0.21$. Older adults had a slightly but not significantly lower preferred frequency ($M = 1.03$ Hz, $SEM = 0.01$ Hz, Range 0.84-1.39 Hz) than younger adults ($M = 1.17$ Hz, $SEM = 0.02$ Hz, Range 0.90-1.77 Hz) but a significantly lower frequency (older, $M = 1.17$ Hz, $SEM = 0.02$ Hz, Range 0.94-1.45 Hz; young, $M = 1.54$ Hz, $SEM = 0.02$ Hz, Range 1.02-1.87 Hz) when moving as-fast-as possible. There were also significant interactions between GROUP and LIMB, $F(1, 30) = 8.44, p = .007, \eta p^2 = 0.22$, and GROUP and TASK, $F(1, 30) = 4.60, p = .04, \eta p^2 = 0.13$, which were qualified by significant GROUP x TASK x FREQUENCY, $F(1, 30) = 10.01, p = .004, \eta p^2 = 0.25$, and GROUP x LIMB x FREQUENCY interactions, $F(1, 30) = 8.65, p = .006, \eta p^2 = 0.22$. As can be seen in Figure 5.2, overall movement frequencies were significantly higher in fast-as-possible conditions than preferred conditions ($ps < .001$). A group difference was observed in the fast-as-possible condition in both single- and dual-tasks with the younger group showing higher movement frequency than the older group. Although the older group did not show any difference between single- and dual-task conditions ($ps > 0.57$), the

younger group performed the fast-as-possible condition at a higher frequency under dual-task than single-task conditions ($p < .001$).



older adults when moving at preferred (PRF) speed and fast-as-possible (FAP) speed.

Similarly, overall movement frequencies were significantly higher in fast-as-possible conditions than preferred conditions ($ps < .001$) as expected (Figure 5.3). The group difference was observed in both upper and lower limb, fast-as-possible condition with the younger group showing higher movement frequency than the older group, while there were no significant movement frequency differences between groups at preferred speed condition ($ps > .88$). Although the younger group did not show any movement frequency

differences between upper and lower limb for neither of movement frequency conditions, older adults moved their upper limb significantly faster than their lower limb in fast-as-possible condition ($p < .001$).

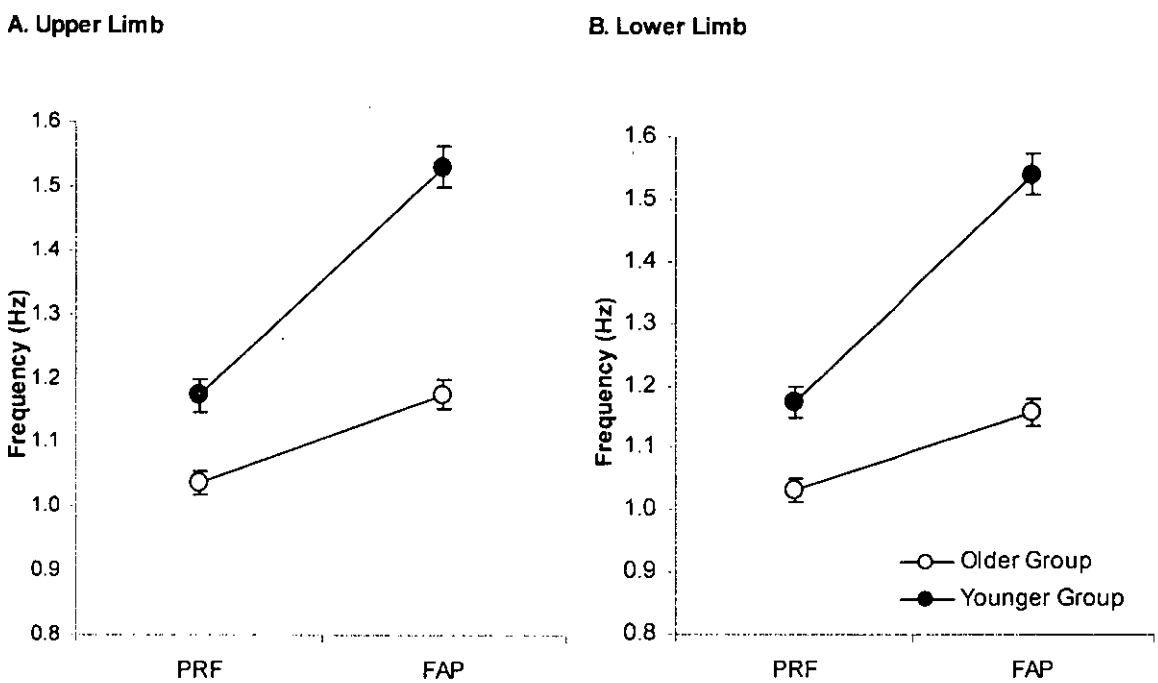


Figure 5.3 Mean movement frequency of A. Upper and B. Lower limbs for young and older adults when moving at preferred (PRF) speed and fast-as-possible (FAP) speed.

There was a significant main effect of LIMB COMBINATION, $F(1, 30) = 6.22$, $p = .018$, $\eta p^2 = 0.17$, and a significant GROUP x LIMB COMBINATION interaction, $F(1, 30) = 5.00$, $p = .033$, $\eta p^2 = 0.14$, showing that in younger adults coordination patterns involving contralateral limbs were executed at a higher frequency than ipsilateral limb patterns,

whereas in older adults similar frequencies were used for both limb combinations (Figure 5.4).

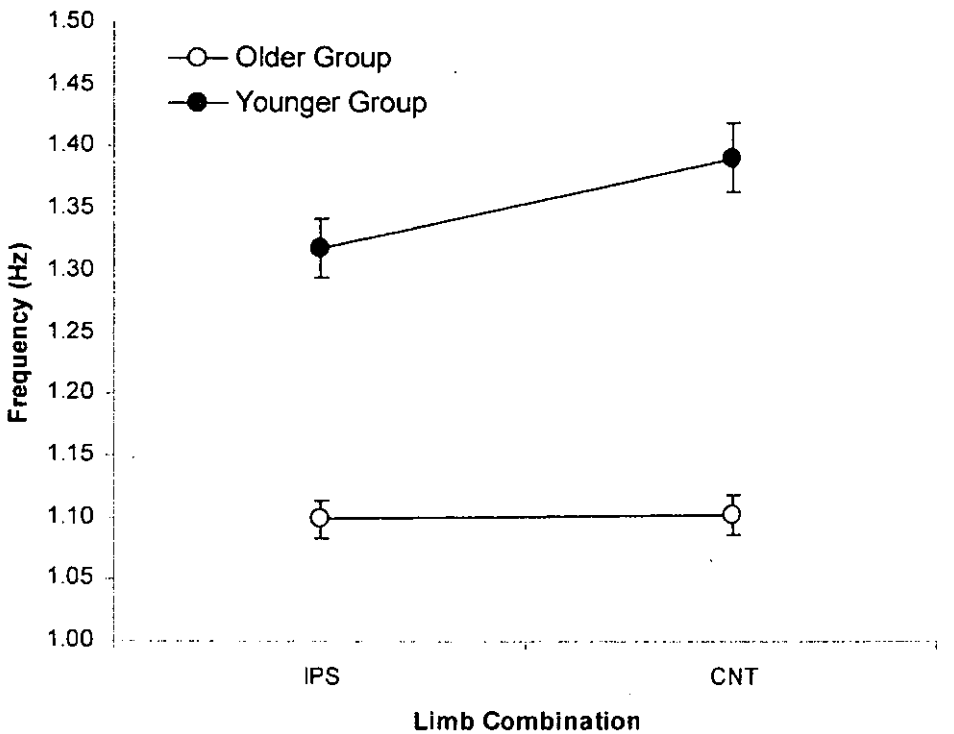
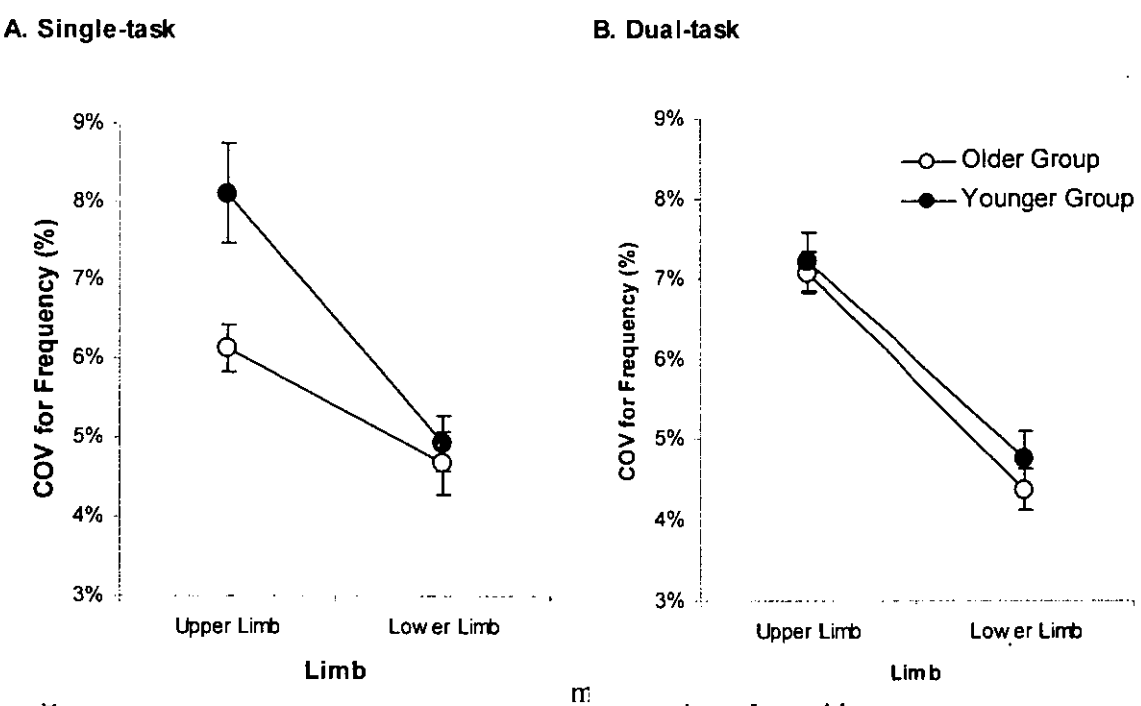


Figure 5.4 Mean movement frequency for younger and older adults during ipsilateral (IPS) and contralateral (CNT) limb combination.

Variability of Frequency. The coefficient of variation for frequency was analyzed by employing a 2 x 2 x 2 x 2 x 2 (GROUP x TASK x LIMB x LIMB COMBINATION x FREQUENCY) ANOVA. There was a significant main effect of FREQUENCY, $F(1, 30) = 23.52$, $p < .001$, $\eta p^2 = 0.44$, indicating that the variability of movement frequency was higher during fast-as-possible movements ($M = 6.62$ %, $SEM = 0.24$ %) than preferred

speed movements (M = 5.18 %, SEM = 0.16 %). There were also significant main effects of LIMB, F (1, 30) = 49.91, p < .001, ηp^2= 0.62, and LIMB COMBINATION, F (1, 30) = 10.90, p = .002, ηp^2= 0.27. These main effects were involved in higher order interactions. A significant interaction of GROUP x TASK x LIMB, F (1, 30) = 5.39, p = .027, ηp^2= 0.15, revealed that upper-limb movements showed higher variability in movement speed compared to lower-limb movements across tasks and groups (ps < .035) (Figure 5.5). The source of the interaction appears to be that for the older group variability of upper-limb movement frequency increased from single- to dual-task trials, while the younger group showed a decrease in upper-limb variability from single to dual-task trials. However, none of the post-hoc comparisons were significant (ps > .352).



younger and older adults in A. Single-task and B. Dual-task.

There was also a significant interaction of GROUP x LIMB x LIMB COMBINATION, F (1, 30) = 5.18, p = .030, ηp^2= 0.15. Although, upper-limb movements exhibited higher variability than lower-limb movements for participants in both groups and limb combinations, lower-limb movements of the younger group showed higher coefficient of variation during ipsilateral limb movements than contralateral limb coordination (Figure 5.6). The differences between young and older adults were not significant (p > .90).

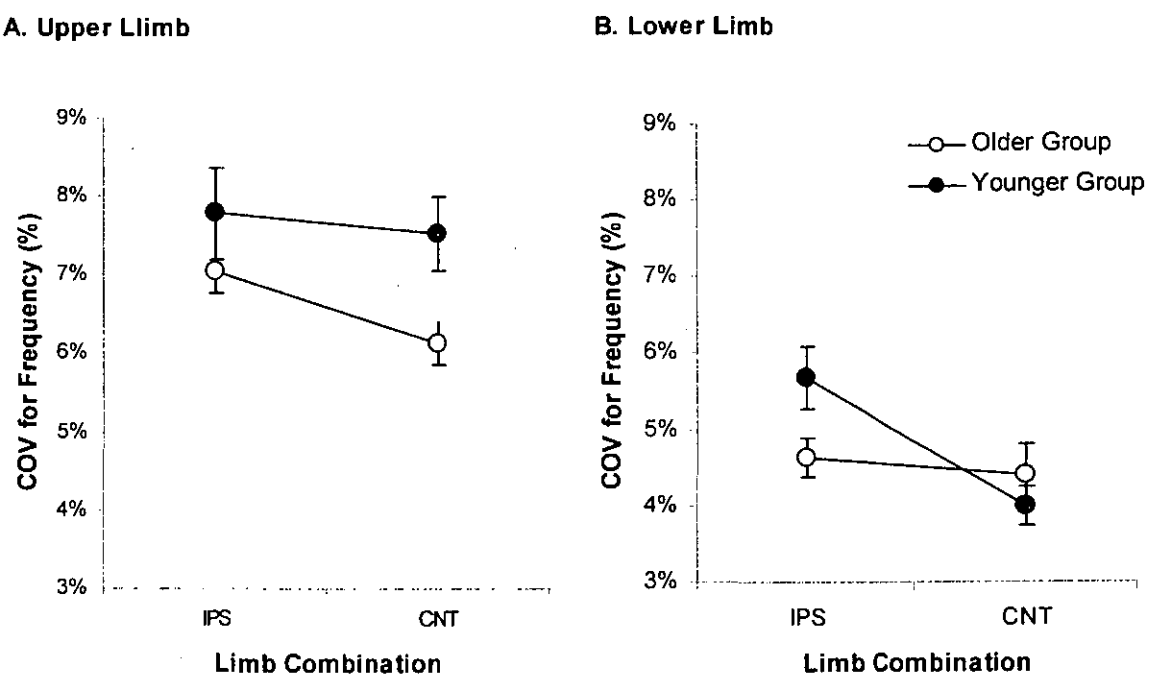


Figure 5.6 Coefficient of variation for movement frequency of A. Upper- and B. Lower-limb for younger and older adults with ipsilateral (IPS) and contralateral (CNT) limb combination.

Amplitude. Mean amplitude was analysed using a 2 x 2 x 2 x 2 x 2 (GROUP x TASK x

LIMB x LIMB COMBINATION x FREQUENCY) ANOVA. Significant main effects of GROUP, $F(1, 30) = 16.85$, $p < .001$, $\eta p^2 = 0.36$, TASK, $F(1, 30) = 17.61$, $p < .001$, $\eta p^2 = 0.37$, LIMB, $F(1, 30) = 105.86$, $p < .001$, $\eta p^2 = 0.78$, and LIMB COMBINATION, $F(1, 30) = 13.33$, $p = .001$, $\eta p^2 = 0.31$, were involved in higher order interactions. There was a significant interaction of GROUP x LIMB COMBINATION, $F(1, 30) = 9.40$, $p = .005$, $\eta p^2 = 0.24$, indicating that the younger group significantly decreased movement amplitude in the contralateral limb combination, in comparison to the ipsilateral limb combination (Figure 5.7). Young adults also demonstrated significantly lower movement amplitude in the contralateral limb combination in comparison to the older group.

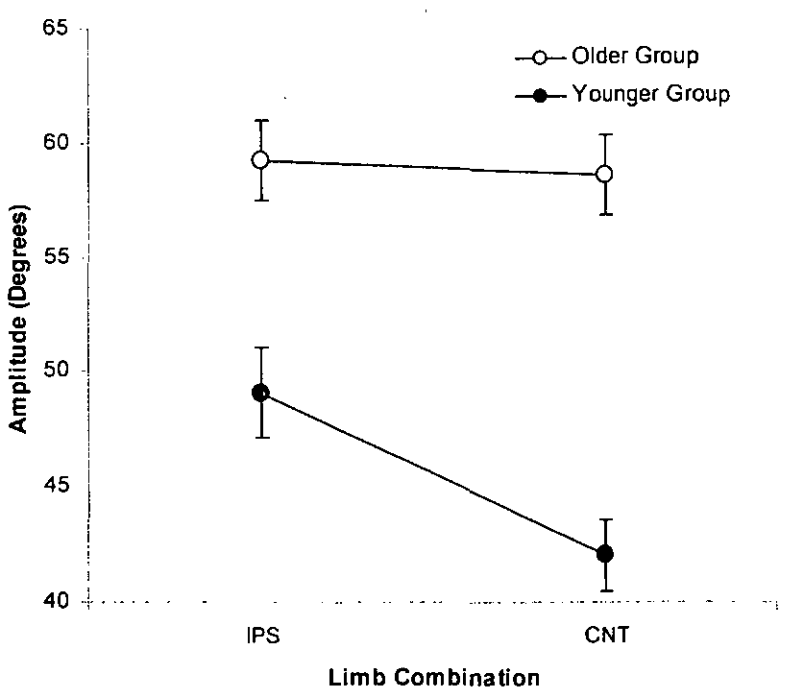


Figure 5.7 Mean movement amplitude during ipsilateral (IPS) and contralateral (CNT) limb combination for younger and older adults.

There was also a significant interaction of GROUP x TASK x LIMB, $F(1, 30) = 10.42$, $p = .003$, $\eta p^2 = 0.26$. However, none of the post-hoc comparisons for group differences were significant ($ps > .228$). Overall, lower-limb movement amplitude was significantly larger than upper-limb movement amplitude for both younger and older adults. The general patterns of two age groups were different. As illustrated in Figure 5.8, younger participants significantly reduced their amplitude from single-task to dual-task in both upper-limb and lower-limb. In contrast, older adults showed consistent movement amplitude across tasks for both upper- and lower-limbs.

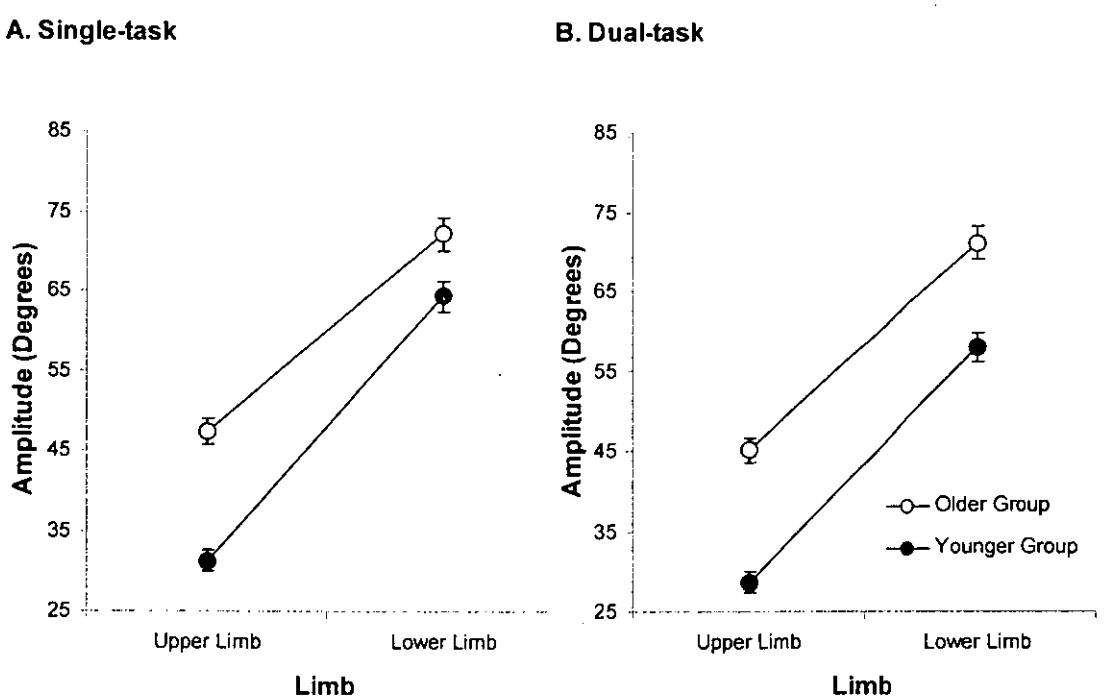


Figure 5.8 Mean movement amplitude of upper- and lower-limb for younger and older adults in A. Single- and B. Dual-task.

Standard Deviation of Amplitude. Standard deviation of amplitude was analysed using a 2 x 2 x 2 x 2 x 2 (GROUP x TASK x LIMB x LIMB COMBINATION x FREQUENCY) ANOVA. Movement amplitude was more variable in single- (M = 4.06°, SEM = 0.11°) than dual-task conditions (M = 3.72°, SEM = 0.08°), F (1, 30) = 10.72, p = .003, ηp^2= 0.26, and the amplitude of lower-limb movements was more variable (M = 3.36°, SEM = 0.07°) than upper-limb movements (M = 3.21°, SEM = 0.07°), F (1, 30) = 49.12, p < .001, ηp^2= 0.62. There was a main effect of FREQUENCY, F (1, 30) = 22.78, p < .001, ηp^2= 0.43, indicating that amplitudes were more variable at faster movement frequencies (M = 4.18°, SEM = 0.10°) than slower movement frequencies (M = 3.61°, SEM = 0.07°).

5.3.2 Relative phase measures

Absolute Error (AE) of Relative Phase. The analysis of relative phase absolute error revealed a significant main effect of FREQUENCY, F (1, 30) = 42.29, p < .001, ηp^2= 0.59, with the target phase relationship between the limbs being less accurately produced when participants attempted to go fast-as-possible (M = 29.10°, SEM = 1.46°) than at their preferred speed (M = 16.26°, SEM = 0.99°). There was also a significant GROUP x LIMB COMBINATION x FREQUENCY interaction, F (1, 30) = 6.34, p = .017, ηp^2= 0.17. While older adults showed a similar reduction in pattern accuracy with increased cycling

frequencies for both ipsilateral and contralateral limb combinations for younger adults the effect of movement speed produced a greater loss of accuracy when coordinating ipsilateral than contralateral limbs (Figure 5.9).

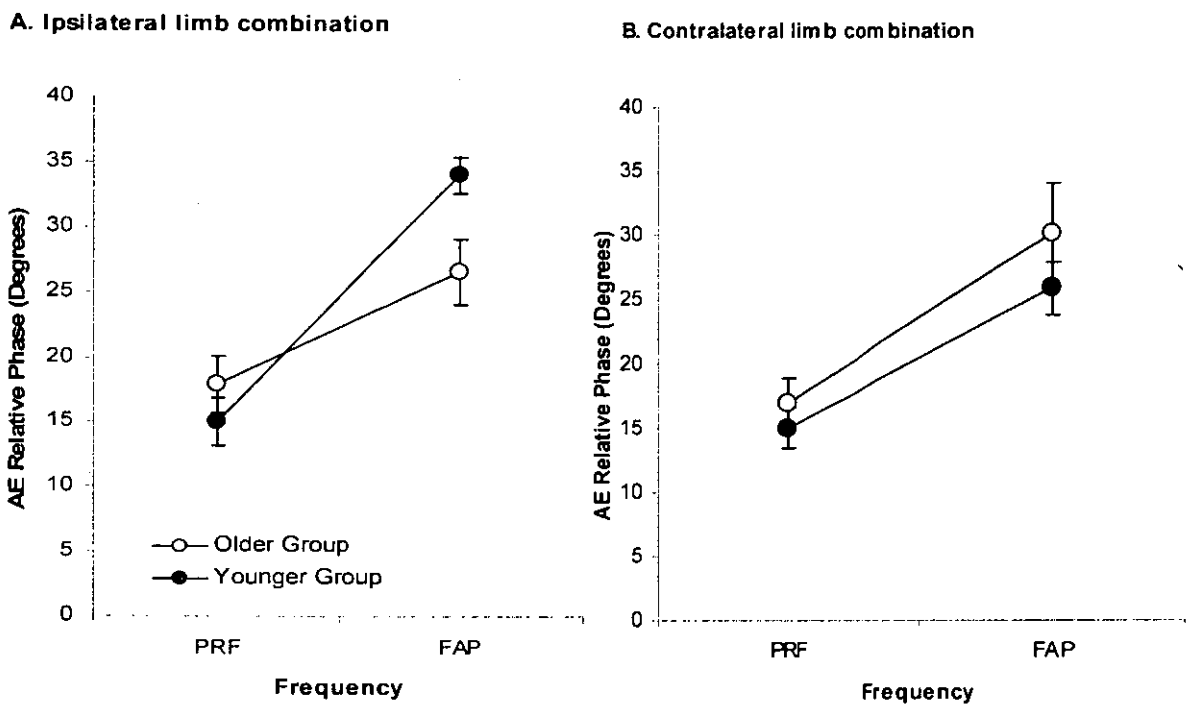


Figure 5.9 Absolute error of relative phase for younger and older adults as a function of limb combination (A. Ipsilateral limb combination, B. Contralateral limb combination) when moving at preferred (PRF) and fast-as-possible (FAP) frequencies.

Standard Deviation (SD) of Relative Phase. Analysis of the SD of relative phase showed significant main effects of LIMB COMBINATION, $F(1, 30) = 11.06$, $p = .002$, $\eta p^2 = 0.27$, and FREQUENCY, $F(1, 30) = 23.17$, $p < .001$, $\eta p^2 = 0.44$. Consistent with previous

findings, contralateral limb coordination (M = 22.89°, SEM = 1.13°) was performed with higher stability than ipsilateral limb coordination (M = 26.66°, SEM = 1.01°), as was performance at preferred frequency (M = 20.99°, SEM = 0.60°) compared to when moving at the faster frequency (M = 28.56°, SEM = 1.33°). There was no significant main effect or interaction involving GROUP ($p > .43$). Thus, allowing participants to select their movement speeds produced similar levels of coordination task performance between the two groups.

5.3.3 Behavioural Data: Visual Task

Preliminary analyses were conducted on RT for correct responses and the number of target stimuli correctly detected using 2 (GROUP) x 2 (TASK) ANOVAs. Older adults showed longer reaction times (M = 439.38 ms, SEM = 12.52 ms) to target stimuli than younger adults (M = 390.70 ms, SEM = 10.62 ms), F (1, 30) = 7.72, p = .009, ηp^2= 0.20, and responses in the single-task condition (M = 378.30 ms, SEM = 8.56 ms) were significantly faster than when the two tasks were performed together (M = 451.78 ms, SEM = 12.13 ms), F (1, 30) = 89.14, $p < .001$, ηp^2= 0.75. There was an interaction between GROUP and TASK, F (1, 30) = 4.51, p = .042, ηp^2= 0.13, showing that the difference

between the two groups was larger in the dual-task than the single-task conditions (see Figure 5.10).

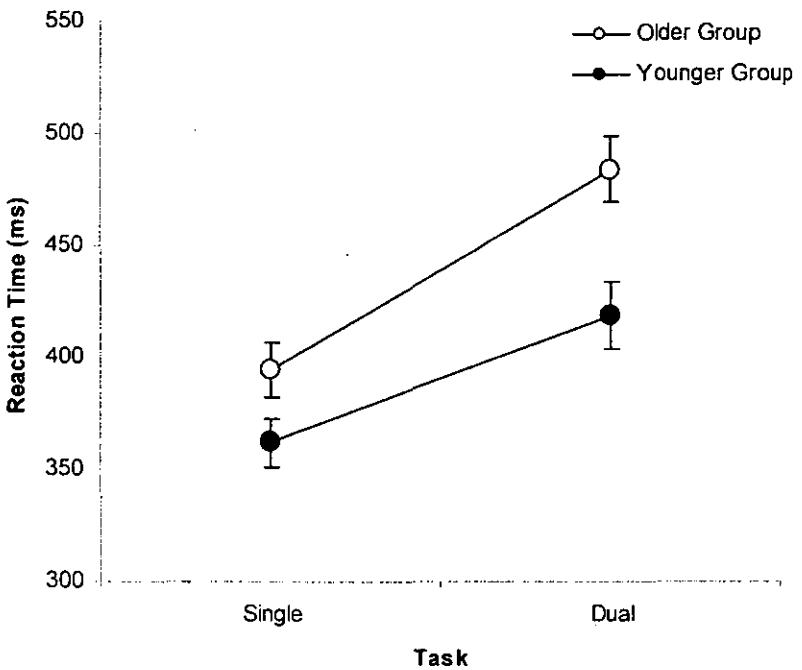


Figure 5.10 Mean reaction time for younger and older adults in single-task and dual-task conditions.

Analysis of the number of target stimuli correctly detected indicated similar levels of accuracy for younger and older adults during both single- (younger, $M = 26.56$, $SEM = 0.57$: older, $M = 26.81$, $SEM = 0.44$) and dual-task conditions (young, $M = 25.70$, $SEM = 0.38$; older, $M = 25.92$, $SEM = 0.27$). Overall, accuracy was slightly higher during single-task ($M = 26.69$, $SEM = 0.35$) than dual-task trials ($M = 25.81$, $SEM = 0.23$), $F(1, 30) = 5.21$, $p = .030$. $\eta p^2 = 0.15$.

A comparison of mean RTs across the dual-task conditions gave significant main effects of GROUP, F (1, 30) = 9.11, p = .005, ηp^2= 0.23, and LIMB COMBINATION, F (1, 30) = 18.61, p = .001, ηp^2= 0.38. Reaction times for the older group (M = 484.38 ms, SEM = 14.88 ms) and during coordination of ipsilateral limbs (M = 460.64 ms, SEM = 8.78 ms) were slower than for the younger group (M = 419.18 ms, SEM = 15.20 ms) and during contralateral limb coordination (M = 442.92 ms, SEM = 9.00 ms). There were no significant interactions involving GROUP as a factor..

Analysis of visual task accuracy during dual-task trials gave only a main effect of LIMB COMBINATION, F (1, 30) = 8.75, p = .006, ηp^2= 0.23. On average slightly fewer targets were detected during trials in which the coordination task involved ipsilateral (M = 25.33, SEM = 0.37) rather than contralateral limbs (M = 26.30, SEM = 0.27).

5.3.4 Electrophysiological data

Grand mean averaged waveforms for the two groups for frontal, central, and parietal sites are presented in Figure 5.11. As preliminary analyses of peak amplitude and latency of P300 components showed limited activity in lateral sites, further analyses were conducted only on the midline electrodes (Fz, Cz, Pz).

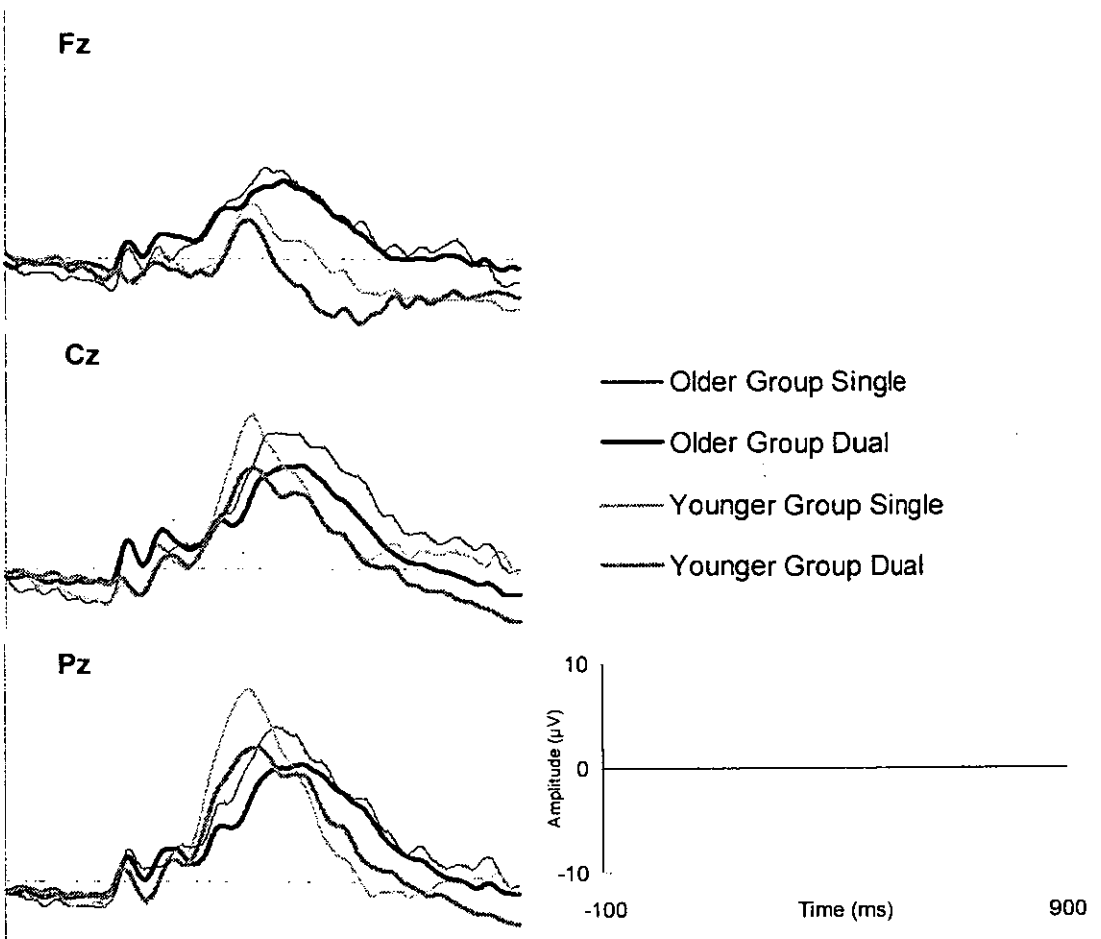


Figure 5.11 Grand mean averages in the single- and dual-task conditions for the younger and older groups at frontal, central, and parietal sites.

P300 amplitude. A 2 (GROUP) x 2 (TASK) x 3 (MIDLINE SITE: frontal, central, parietal) ANOVA was used to examine differences in P3b amplitude between single- and dual-task conditions. Amplitudes to target stimuli were significantly higher during single visual task

performance (M = 14.09 μV, SEM = 0.62 μV) than when the visual task was performed concurrently with the coordination task (M = 10.88 μV, SEM = 0.46 μV), F (1, 30) = 17.92, p < .001, ηp^2= 0.37. There was a main effect of MIDLINE SITE F (1, 30) = 33.79, p < .001, ηp^2= 0.53, and a TASK x MIDLINE SITE interaction, F (1.98, 59.50) = 5.08, p = .009, ηp^2= 0.14, showing that for both single- and dual-task trials, respectively, the frontal P3 (single, M = 10.48 μV, SEM = 0.99 μV; dual M = 8.33 μV, SEM = 0.62 μV) was smaller than the central P3 (single, M = 15.22 μV, SEM = 1.02 μV, dual, M = 11.38 μV, SEM = 0.74 μV) which was smaller than the parietal P3 (single, M = 16.56 μV, SEM = 0.95 μV; dual, M = 12.92 μV, SEM = 0.81 μV). Of particular interest was a significant interaction between GROUP and MIDLINE SITE, F (1.57, 47.09) = 8.39, p = .001, ηp^2= 0.22, shown in Figure 5.12. Post-hoc analyses revealed that P3 amplitudes did not differ across midline sites in older adults, whereas in younger adults frontal P3 was significantly smaller than central P3 and parietal P3. The interaction between GROUP, TASK and MIDLINE SITE was also significant, F (1.98, 59.50) = 3.39, p = .040, ηp^2= 0.10. While the same pattern of P3 amplitudes revealed in the two-way interaction was evident for both tasks, the increase in amplitude between frontal and central sites in older adults was larger during single- than dual-task trials.

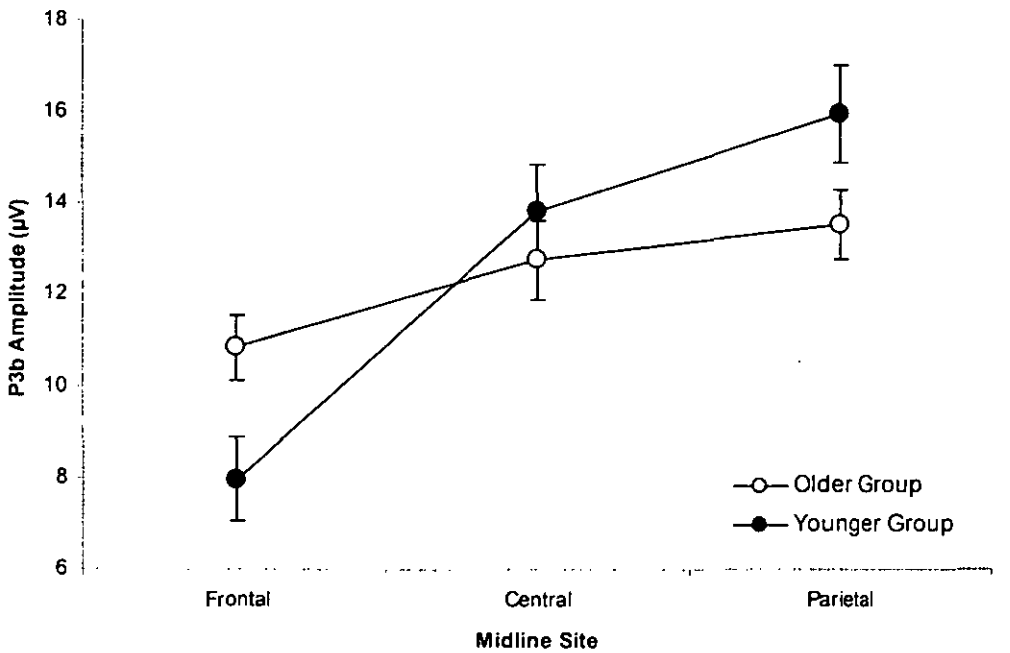


Figure 5.12 Mean P3b amplitude for younger and older adults in frontal, central, and parietal cites.

A separate 2 (GROUP) x 2 (LIMB COMBINATION) x 2 (FREQUENCY) x 3 (MIDLINE SITE) ANOVA performed on the dual-task trials revealed a significant main effect of MIDLINE SITE, $F(1.55, 46.38) = 27.97$, $p < .001$, $\eta p^2 = 0.48$, and a GROUP x MIDLINE SITE interaction, $F(1.55, 46.38) = 5.22$, $p = .008$, $\eta p^2 = 0.15$, showing the same pattern of amplitudes as that obtained in the aforementioned analysis. In older adults P3 amplitudes did not differ across midline sites (Frontal, $M = 9.06$ μV, $SEM = 0.40$ μV; Central $M = 10.56$ μV, $SEM = 0.47$ μV; Parietal, $M = 11.76$ μV, $SEM = 0.46$ μV), whereas in younger adults all three sites were significantly different showing frontal-parietal

increases ((Frontal, $M = 7.59$ μV, $SEM = 0.69$ μV; Central $M = 12.20$ μV, $SEM = 0.75$ μV; Parietal, $M = 14.08$ μV, $SEM = 0.77$ μV).There was also a significant interaction between GROUP, MIDLINE SITE and FREQUENCY, $F(2, 60) = 4.93$, $p = .010$, $\eta p^2 = 0.14$. However, post-hoc comparisons revealed non-meaningful differences.

P300 latency. The 2 (GROUP) x 2 (TASK) x 3 (MIDLINE SITE) ANOVA conducted on P3 latency revealed that the P3 component peaked earlier for younger adults ($M = 404.46$ ms, , $SEM = 6.11$ ms) than for older adults ($M = 447.71$ ms, $SEM = 5.72$ ms), $F(1, 30) = 7.28$, $p = .011$, $\eta p^2 = 0.20$, and earlier for single-task ($M = 407.54$ ms, $SEM = 6.47$ ms) than for dual-task trials ($M = 444.63$ ms, $SEM = 5.54$ ms), $F(1, 30) = 18.04$, $p < .001$, $\eta p^2 = 0.38$. No other main effects or interactions were significant.

A separate 2 (GROUP) x 2 (LIMB COMBINATION) x 2 (FREQUENCY) x 3 (MIDLINE SITES) performed on the dual-task trials did not show any significant main effects or interactions ($p > .111$)

5.4 Discussion

To investigate the age-related changes in the central cost of interlimb coordination a dual-task paradigm was employed and kinematic measures associated with interlimb

coordination, behavioural reaction time, and ERPs were assessed. From the analyses of coordination performance, evidence for age-related motor slowing was observed with older adults exhibiting a significantly slower movement frequency than younger adults when asked to make coordinated movements of an arm and leg as fast as possible. When moving as fast as possible younger adults performed the contralateral limb combination at a higher frequency and with smaller movement amplitudes than the ipsilateral limb combination, whereas older adults produced equivalent movement speed and amplitude across the two limb combinations. Allowing participants to self-determine the preferred and fast-as-possible frequencies resulted in similar levels of coordination performance between younger and older adults. For both groups of participants, coordination pattern accuracy and stability decreased at the faster movement frequency and the stability of patterns produced with ipsilateral limbs was lower than when contralateral limbs were used.

The equivalent coordination task performance between younger and older adults is an important result as it allowed us to evaluate age-related differences in behavioural and neurophysiological measures of attentional load at similar levels of task difficulty. The older group had longer reaction times than the younger group to visual task target stimuli during single-task performance consistent with a general slowing with age. While both

groups showed an increase in visual task RT when the limb coordination task was performed concurrently, the dual-task effect was larger for the older group than for the younger group. As the age effect in dual-task cost was larger than would be expected from the age difference evident in single-task performance, it is unlikely to be solely accounted for by a general slowing explanation (Van der Lubbe & Verleger, 2002; Verhaeghen, 2003 ski, & Cerella, 2003).

An interesting finding was that the age-related differences in visual task reaction time were similar across dual-task conditions. That is, reaction time in older adults was longer by a similar amount for factors that influenced (i.e., limb combination) or did not influence (i.e., frequency) dual-task costs in younger adults. The absence of age by condition interactions for a variety of moderating variables has also been reported in a meta-analysis of dual-task performance suggesting that age-related differences may reflect a general deficit in the ability of older people to perform two tasks concurrently (Verhaeghen, 2003).

As expected, the behavioural measure of attentional load, response time to visual task target stimuli, indicated that the central cost of having to perform a concurrent interlimb coordination task was greater than performing only the visual task. The

neurophysiological index of central resource allocation, P3b amplitude, was consistent with this interpretation showing reduced P3b amplitude in dual-task conditions compared to the single-task condition. However, the amplitude of P3b did not differ across manipulations of primary task difficulty. The lack of a task difficulty effect may reflect that the manipulations in the present study involved response related processes (i.e., limb combination, frequency) rather than the demanding perceptual-central resources to which P3b amplitude is more sensitive (Kok, 2001).

Older participants had significantly longer visual task reaction times than younger participants and P3b amplitudes showed a significant GROUP x MIDLINE SITE interaction. While younger adults showed the expected centro-parietal distribution, P3b amplitudes in older adults did not differ across the three midline sites showing lower amplitudes than younger adults at central and parietal sites but a higher amplitude at the frontal site. The higher amplitude in older adults at the frontal site is interesting and is consistent with some recent fMRI studies of ipsilateral limb coordination where additional activation was observed in older adults in areas possibly relating to the cognitive monitoring of performance including the prefrontal cortex (Heuninckx et al., 2005; Heuninckx et al., 2008). Thus, the present research supports the emerging view that in order

to perform motor tasks as well as younger individuals, older people may recruit additional non-motor areas to compensate for age-related decline in brain function (e.g., Cabeza et al., 2002; Heuninckx et al., 2008; Reuter-Lorenz & Lustig, 2005).

Consistent with previous studies, the P3b latencies of older adults were longer than those of younger adults (e.g., Bashore, Osman, & Heffley, 1989; Christensen, Ford, & Pfefferbaum, 1996; Fjell & Walhovd, 2001; Polich, 1996; Van der Lubbe & Verleger, 2002; Yordanova et al., 2004) and longer latencies were observed for both groups in dual-task compared to single-task conditions (Matthews et al., 2006). Age, however, was not involved in significant interactions with any of the other variables manipulated in the present study. Although it is tempting to relate the age-related differences in reaction time and P3b latency, the relationship between response latency and the latency of the P3b component of the ERP remains controversial (Bashore et al., 1989; Polich, 2007; Verleger, 1997). For example, recent studies measuring ERPs in younger and older adults during choice reaction time tasks have suggested that age-related slowing in these tasks is not due to delays in the stimulus processing and response selection stages of processing. Rather the age-related delay in reaction time appeared to be located in the response-generation stage with older adults requiring longer and stronger activation of the contralateral motor cortex

to initiate movement (Falkenstein et al., 2006; Yordanova et al., 2004).

In the present study coordination task performance deteriorated with increased frequency and when ipsilateral limbs were coordinated. The breakdown of non-isodirectional coordination with increased frequency is consistent with previous studies of interlimb coordination showing a phase transition to the preferred isodirectional coupling between limbs at high frequencies (Baldissera, Cavallari, & Civaschi, 1982; Baldissera, Cavallari, Marini, & Tassone, 1991). There is also physiological evidence of interactions within the motor cortex that may facilitate isodirectional coupling between ipsilateral hand and foot areas when the two limbs are moved together (Byblow et al., 2007; Liepert, Terborg, & Weiller, 1999) and through subliminal postural co-activations of the hand when only the foot is moved (e.g., Baldissera & Esposti, 2005; Borroni, Cerri, & Baldissera, 2004). Thus, non-isodirectional coordination of ipsilateral limbs would require the suppression of intracortical connections favouring isodirectional coupling between hand and foot areas.

Reaction time and accuracy to secondary task target stimuli also indicated that coordinating limbs on the same side of the body (ipsilateral) was more difficult for both groups of participants than coordinating contralateral limbs. Limb combination, however,

did not differentially affect the amplitude of the P3b component of the ERP, suggesting that the longer visual task reaction time during ipsilateral limb coordination did not reflect an increased demand for perceptual-central resources. As reaction time involves both central and response processes, it is possible that the longer reaction time reflected interference between response-related processes involved in the two tasks. In dual-task trials participants were required to press a button with their left index finger to visual task target stimuli while simultaneously producing cyclical non-isodirectional coordination movements with either the right arm and leg or the right arm and left leg. There are previous reports that simple reaction time is delayed when the contralateral hand is simultaneously carrying out another motor task (Begeman et al., 2007; Buenaventura & Sarkin, 1996; Castellote, Valls-Sole, & Sanegre, 2004). Transcallosal inhibition is one possible physiological mechanism that may underlie the delay in reaction time under dual-task conditions. Sohn et al. (2003) used transcranial magnetic stimulation (TMS) to demonstrate that voluntary phasic contraction of a hand muscle produced inhibition of the homologous and adjacent muscles of the contralateral hand. It is possible that when the concurrent movements involved effectors controlled within the same hemisphere (i.e., ipsilateral limb combination) a greater level of transcallosal inhibition was imposed on the

contralateral hand than when the contralateral limbs were being coordinated, thereby delaying visual task reaction time to a greater extent during ipsilateral limb coordination.

In conclusion, when task difficulty was equated between groups of participants, older adults performed the non-isodirectional interlimb coordination at the same level as the younger adults. Age-related differences in secondary task reaction time and P3b amplitude, however, suggested that older adults rely more on cognitive control of their movements than younger adults, perhaps as a compensation for deficits in the processing of sensory feedback with age. For both groups of participants coordinating ipsilateral limbs was more difficult and produced longer secondary task reaction times than coordinating contralateral limbs. P3b amplitude, however, did not differ between the two coordination conditions suggesting that the elevated secondary task reaction time when coordinating limbs on the same side of the body may reflect some form of structural interference between motor processes involved in the primary and secondary tasks.

Chapter 6 Literature Review (Part 3)

Age-related Differences in Cortical Inhibitory Processes during Interlimb Coordination

The empirical study in Part 2 of the thesis examined age-related changes in the central resource allocation during interlimb coordination. A dual-task paradigm was employed in which the amplitude of the P3b component of the ERPs was used as an index of the amount of central resources required to perform the interlimb coordination task. The behavioural measure of attentional load, probe RT, indicated that older adults required more central resources compared to younger adults when performing interlimb coordination tasks. Analysis of P3b amplitude indicated that brain activation patterns may change with advancing age with older adults displaying consistent P3b amplitudes across midline sites while younger adults showed increased P3b amplitude towards the central and parietal sites. There is evidence from previous studies, however, of higher levels of cognitive control of movement with age (Heuninckx et al., 2005; Heuninckx et al., 2008). Thus the results of Part 2 are consistent with the view that the regulation of interlimb coordination performance in the aged brain may shift to greater conscious control (Lindenberger et al., 2000).

Part 3 of the research investigated the hypothesis that age-related changes in

interlimb coordination are related to a decline in the control of cortical inhibition. It has been suggested that a decreased ability to control the balance between facilitatory and inhibitory processes compromises task performance in older adults. Behavioural studies examining the effect of aging on interlimb coordination patterns suggest that older adults have difficulty inhibiting the preferred intrinsically stable in-phase pattern (Greene & Williams, 1996; Heuninckx et al., 2005; Heuninckx et al., 2008). However, the contribution of cortical inhibition to interlimb coordination in older adults has been rarely explored. Therefore, Part 3 of the research investigated the modulation of cortical inhibitory process during interlimb coordination.

6.1 Age-Related Changes in Inhibitory Processes

On a conceptual level, it has been argued that a degraded ability for inhibitory control is a primary cause of declined cognitive task performance (Burke, 1997; Hasher & Zacks, 1988; Kane et al., 1994; Kramer et al., 1994; Zacks, Hasher, & Li, 2000) and motor performance (Dustman et al., 1996; Dustman et al., 1993). This hypothesis is based on the view that enhanced top-down control can improve performance in situations where performance is degraded by other factors. That is, to some extent, one can reduce performance decline by increasing attention to task relevant stimuli or by inhibiting task irrelevant information

(Hasher, Quig, & May, 1997). Top-down executive functions that organize inhibitory functioning, scheduling, planning, and task switching are cognitive functions most susceptible to the process of aging (Colcombe, Kramer, Erickson, & Scalf, 2005). Executive functions are believed to be largely subserved by the frontal lobes of the brain (West, 1996), which are compromised by aging process to a greater extent than other regions of the brain (Raz, 2000; Resnick, Pham, Kraut, Zonderman, & Davatzikos, 2003). Neurophysiological studies using fMRI also demonstrate additional brain activation especially in frontal areas older adults when participants are required to suppress irrelevant processing (e.g., Milham et al., 2002; Nielson et al., 2002). Using fMRI, Neilsen et al. (2002), for example, investigated age-related changes in inhibitory control in a task requiring participants to respond to the letters 'X' and 'Y' when presented alternately, while consecutive presentations of same letters required no response. They found increased neural activity predominantly in right prefrontal and parietal regions and more extensive bilateral and prefrontal activity in older adults who successfully performed the task. The authors concluded that the additional activation in successful older adults was evidence of a compensatory mechanism to overcome declined inhibitory function. In contrast to cognitive tasks, the extent to which inhibitory function contributes to the regulation of interlimb

coordination tasks is not well understood. Age-related changes in the physiological aspect of inhibitory function will be outlined in the section 6.3. At the level of motor cortex inhibitory processes operating on individual muscles have been extensively studied using transcranial magnetic stimulation (TMS), a technique that can be used to investigate the physiological functioning of the corticospinal system. Recently, cortical inhibition mediated by gamma-aminobutyric acid (GABA)-ergic activity has been implicated in the control of inhibitory functions during a motor task. In the current research, TMS was employed to examine cortical inhibition during interlimb coordination.

6.2 Transcranial Magnetic Stimulation: Overview

TMS can be used to investigate different aspects of brain function. In this section, the basic mechanism of motor cortex stimulation by TMS is introduced followed by a section that outlines the measures of cortical function relevant to the present research.

Basic mechanism of motor cortex stimulation. Transcranial magnetic stimulation (TMS) is a non-invasive, painless, and safe electrophysiological technique that allows investigation of cortical networks in humans (Hallett, 2000; Rothwell, 1997) (Figure 6.1). The technique involves producing a perpendicular magnetic field through a metal coil held over the scalp that induces a rapidly changing magnetic field with lines of flux running perpendicular to

the coil. The change of magnetic field induces an electrical ionic current in the cortex, which causes depolarization including an action potential or excitatory (or inhibitory) postsynaptic potential by penetrating the membranes of the neurons (for a detail see Ilmoniemi, Ruohonen, & Karhu, 1999; Rothwell, 1997; Terao & Ugawa, 2002).

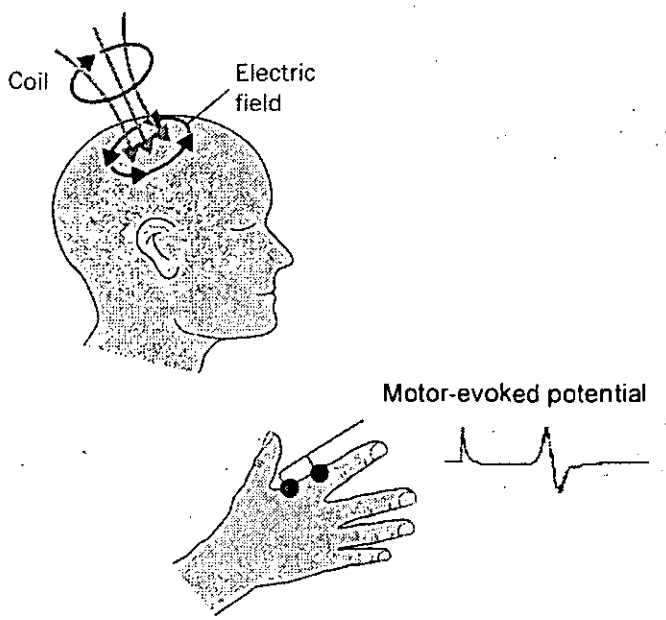


Figure 6.1 Schematic illustration of TMS and evoked muscle response from a hand muscle (adapted from Kobayashi & Pascual-Leone, 2003)

There are preferential sites of neural activation by TMS. Generally favoured points of stimulation where greatest potential changes in the membrane induced are at bends or terminations of axons (Ilmoniemi et al., 1999). At these points axons cross the electric field which results in depolarization of the axon membrane (Rothwell, 1997). At the muscle level, brain stimulation by TMS of the motor cortex results in a motor evoked

potential (MEP) in contralateral extremity muscles (Pascual-Leone et al., 1998). When neurons in the pyramidal tract are electrically stimulated, descending volleys can be observed. The early spikes of these volleys are called direct or D-waves, which are possibly induced by direct activation of pyramidal tracts either at the initial segment of the neuron, or at proximal internodes in the sub-cortical white matter (Patton & Amassian, 1954). When stimulus intensity is increased, later waves termed indirect or I waves follow the D-wave at an interval of approximately 1.5 ms. These I waves consist of I1, I2, and I3 waves in the order of their latency and are considered as trans-synaptic activation of pyramidal tract neurons (Rothwell, 1997). These multiple volleys are likely to be reflecting repeated firing of pyramidal tract neurons by a single cortical stimulus since only D-waves, but not I waves, were observed after removal of the cortex and under deep amnesia (Patton & Amassian, 1954).

In contrast to electrical stimulation, TMS at threshold excites the pyramidal neurons transsynaptically, which produce I waves in the pyramidal tract preferentially, while electrical stimulation is likely to activate the axons directly to produce D-waves (Rothwell, Thompson, Day, Boyd, & Marsden, 1991). Although it is possible to activate the pyramidal axons by TMS to evoke D-waves, it requires high stimulus intensity (Rothwell, 1997). The

different sites of activation of the corticospinal pathways between electrical stimulation and TMS are reflected in the approximately 2 ms delayed latency of TMS induced response. That is, the latency difference between responses induced by the two stimulations is the time taken for synaptic activation of pyramidal neurons within the motor cortex (Rothwell, 1997). Furthermore, I1 waves are considered to be due to the activation of corticospinal cells by activation of the axons that directly connect to these corticospinal cells, while I2 and I3 waves result from a series of activations of more than one synapse. These transsynpatical activations of the pyramidal tract neurons by magnetic stimulation at threshold intensity are affected by changes in cortical excitability, whereas D-waves evoked by electrical stimulation are less affected (Rothwell, 1997). Therefore, the size of MEPs consisting of I-waves evoked by TMS reflects cortical excitability (Terao & Ugawa, 2002).

The factors which determine the volume of cortical tissue that induce current flows at a significant strength are the size and shape of the coil, intensity of the magnetic field produced though the coil, and the frequency and duration of the delivered magnetic pulses (Anand & Hotson, 2002). There are three major types of coil; circular, figure-of-8, and double-cone coil. The circular coil, usually 14cm in diameter, has a rise time of the electrical pulse of approximately 100 μs with a maximum magnetic field of 1.5 to 2.0 T

along the winding of the coil. It is considered to activate neurons, which lie 1.5 to 2.0 cm below the scalp surface (Epstein, Schwartzberg, Davey, & Sudderth, 1990; Rudiak & Marg, 1994). For more focal stimulation, a figure of 8 coil which has typically two 9 cm coils, was developed. The figure of 8 coil has an advantage of stimulating a more focal area of the cortex with peak field strength generated at the crossing of the coils. Lastly, a double-cone coil also has two 12 cm diameter coils, which are combined at an angle of 90 to 100 degrees. The structure of the cone coil enables magnetic pulses to induce current in deeper parts of the brain, e.g., the leg area of the motor cortex that lies relatively deeper in the interhemispheric fissure at 3 to 4 cm depth from the scalp surface (Terao & Ugawa, 2002).

Using a relatively high frequency, which typically ranges from 1 to 20 Hz or more, TMS has also been used to study functional reorganization of the brain with a technique known as repetitive TMS (rTMS) (Ljubisavljevic, 2006). In the rTMS paradigm stimulus frequencies higher than 5 Hz delivered to a single scalp site increase cortical excitability, whereas lower frequencies lead to suppression of cortical excitability (Chen et al., 1997a; Siebner & Rothwell, 2003). High frequency rTMS has been employed to investigate neural activity during perception, motor execution, and high level cognitive processing (Jahanshahi & Rothwell, 2000) by creating 'virtual lesions' (Walsh &

Rushworth, 1999).

Motor Threshold (MT). Motor threshold (MT) is the minimum intensity of TMS output, which induces a certain level of MEP from a target muscle. The size of the MEP typically used as threshold criteria are 50 μV for a resting muscle and 100 μV for an active muscle (e.g., Chen et al., 1998). MT is considered to reflect primarily changes in neuronal membrane excitability of the motor cortex (Chen et al., 1998). Neuropharmacological studies support this view showing no changes in MT by GABAergic drugs such as benzodiazepines or vigabatrin (Inghilleri, Berardelli, Marchetti, & Manfredi, 1996; Mavroudakis, Caroyer, Brunko, & deBeyl, 1997; Ziemann, Lönnecker, Steinhoff, & Paulus, 1996a, 1996b) and antiglutamatergic drugs such as riluzole (Liepert, Schwenkreis, Tegenthoff, & Malin, 1997), but showing increased MT by sodium channel blockers such as carbamazepine or phenytoin (Chen, Samii, Canos, Wassermann, & Hallett, 1997b; Mavroudakis, Caroyer, Brunko, & Debeyl, 1994; Ziemann, Lönnecker, Steinhoff, & Paulus, 1996a).

Intracortical Inhibition (ICI), Intracortical Facilitation (ICF), and Silent Period (SP). Paired-pulse TMS is a method of measuring the excitability of cortical inhibitory and

excitatory circuits with intracortical inhibition (ICI) and intracortical facilitation (ICF) being the main measures of interest (Kujirai et al., 1993). When a subthreshold conditioning stimulus is delivered 1-4 ms prior to the suprathreshold test stimulus the size of the test MEP is suppressed, which is thought to reflect ICI. When two stimuli are separated by 8-15 ms MEPs are facilitated indexing ICF (Chen et al., 1998). There is strong evidence that ICI takes place at the cortical level. For example, using epidural recording, facilitation of descending volleys by a conditioning stimulus at an interstimulus interval of 20 ms (Kaneko, Kawai, Fuchigami, Shiraishi, & Ito, 1996) and suppression of the descending volleys by subthreshold conditioning at interval less than 5 ms intervals were found (Di Lazzaro et al., 1998). Therefore, the test stimulus can be inhibited by the conditioning stimuli when it is evoked magnetically, whereas electrically evoked test stimulus remains unchanged (Terao & Ugawa, 2002). These results imply that the ICI observed with the magnetical stimulation is due to modulation at the cortical level.

Intracortical inhibition can also be measured by single-pulse TMS. When single-pulse TMS at suprathreshold intensity is applied during voluntary contraction of a muscle, a period of suppressed EMG activity is observed. The initial 50-60 ms of the silent period (SP) in EMG is regarded as being partly due to the refractoriness of the spinal cord and the

latter part of the suppressed period (> 100 ms) as being due to cortical inhibitory processes (Fuhr, Agostino, & Hallett, 1991). The first part of the SP may be due to the muscle twitch caused by TMS modulating the firing of muscle receptors by forcing a pause in spindle firing and withdrawal of Ia excitation which is sensitive to change of muscle length. The late phase of the SP can be explained by intracortical mechanisms including recurrent collaterals from pyramidal tract neurons and activation of the population of cortical inhibitory neurons within the motor cortex. The level of background muscle activation has a minor effect on the duration of the SP, whereas the stimulus intensity linearly increases the duration of the SP (Terao & Ugawa, 2002).

It is considered that ICI and ICF are mediated by $GABA_A$ and glutamate-mediated, respectively (Liepert et al., 1997; Ziemann et al., 1996b), whereas the duration of SP is thought to provide an estimate of $GABA_B$ function (Siebner, Dressnandt, Auer, & Conrad, 1998). Pharmacological interventions have provided evidence of involvement of GABA-ergic interneurons for ICI as measured by TMS. Enhanced ICI was observed by the ingestion of lorazepam, a $GABA_A$ receptor agonist (Ziemann, Lönnecker, Steinhoff, & Paulus, 1996b). Furthermore, Werhahn and colleagues (Werhahn, Kunesch, Noachtar, Benecke, & Classen, 1999) investigated the effects of the blockade of uptake carriers of

GABA on ICI, ICF, and SP by ingesting tiagabine (TGB). Based on the findings of prolonged SP, reduced ICI, and enhanced ICF, the authors concluded that the increased duration of the $GABA_B$ receptor-mediated component results in an increase in SP. In turn, a reduction in ICI reflects inhibition of $GABA_A$ receptor-mediated inhibition through activation of presynaptic $GABA_B$ receptors.

6.3 Age-Related Changes in Intracortical Inhibition

Neurochemical studies using animals suggest that in the aging brain the efficacy of GABA-ergic mediated cortical inhibition is compromised (Caspary et al., 1999; Caspary, Milbrandt, & Helfert, 1995). It is hypothesized that declined intracortical inhibition may be a consequence of diminished neurotransmitter release, diminished production of neurotransmitter, degradation of neurotransmitter receptors, and/or membrane changes (Leventhal, Wang, Pu, Zhou, & Ma, 2003). In humans, age-related changes in the input-output pattern of the motor system have been reported using TMS. Oliviero et al.(2006) compared older and younger adults on several measures of cortical activity including MEP amplitude, short term intracortical inhibition (SICI), and SP. They found smaller MEP amplitude and shorter SP in older adults compared to younger adults, while SICI was comparable in both groups. It was suggested that these changes in excitatory and inhibitory

processes possibly reflect global changes in the motor system with advancing age involving motor cortex, spinal cord, and neuromuscular system. The reduced cortical excitability is likely to be due to decreased synchronization of I-waves and/or recruitment of later I-waves in the descending pathway, a decline in the number of cortical and spinal motoneurones, and declines in the neuromuscular system (Oliviero et al., 2006). The shortening of SP could be attributed to reduced corticospinal outflow, which activates fewer recurrent axon collaterals, and a decreased overall inhibitory effect on corticospinal cells (Orth & Rothwell, 2004). Similarly, Pitcher, Ogston, and Miles (2003) investigated the age-related changes in cortical excitability by using stimulus-response curves. Stimulus-response, or input-output, curves demonstrate a sigmoidal function of MEP amplitude increasing as a function of stimulus intensity. The response to increasing TMS intensity is supposed to reflect excitatory feedback to corticospinal efferent output (Valls-Solé et al., 1994). The results showed that higher stimulus intensities were required in older adults to evoke equivalent size MEP amplitudes to younger adults. A similar result was reported in an examination of cortical activity during different hand movement tasks with smaller MEP areas evident across tasks in older adults compared to younger adults (Sale & Semmler, 2005). Lower cortical excitability in older adults has also been shown in other studies

(Eisen, EntezariTaher, & Stewart, 1996; Eisen, Siejka, Schulzer, & Calne, 1991; Sale & Semmler, 2005), suggesting that a reduced ability to activate motoneurons in the cortical and spinal systems in older adults (Sale & Semmler, 2005).

In contrast to cortical excitability, studies investigating age-related changes in SICI have produced equivocal results. Consistent with the findings of Oliviero et al. (2006), Wassermann (2002) found no reduction in SICI as a function of age in a larger sample. Peinemann and colleagues, however, reported a reduction in SICI in older adults in comparison to younger adults (Peinemann et al., 2001), whereas Kossev et al. (Kossev et al., 2002) found increased SICI in older adults. The latter authors attributed the discrepancy in results across studies to different TMS pulse parameters. That is, the study showing age-related reduction in SICI used a biphasic waveform (Peinemann et al., 2001) whereas those studies reporting no change or an increase in SICI used a monophasic waveform (Kossev et al., 2002; Oliviero et al., 2006; Wassermann, 2002). It has been shown that the monophasic pulse is effective in the situation where current flows in a posterior-anterior direction in the motor cortex, while biphasic stimulation is weaker with the first upstroke in the posterior-anterior direction (Kammer, Beck, Erb, & Grodd, 2001) and is not commonly used for investigating SICI. Even though the monophasic stimulation is widely used to investigate

SICI, increased intracortical inhibition has been reported in only one study (Kossev et al., 2002) with the rest of the studies finding no age differences (Oliviero et al., 2006; Wassermann, 2002). Thus, evidence for age-related changes in SICI, supposedly reflecting changes in intracortical inhibitory processes driven by $GABA_A$ is not conclusive and appears to depend on the parameters of the TMS pulse.

Another measure of cortical inhibition, cortical SP has shown more consistent results with reduced SP duration in older adults being frequently reported (Eisen et al., 1996; Oliviero et al., 2006; Prout & Eisen, 1994; Sale & Semmler, 2005). Sale and Semmler (2005), however, found shorter SP duration compared to younger adults in the non-dominant but not the dominant hand of older adults suggesting that long-term use of the dominant hand may prevent the loss of $GABA_B$ mediated inhibition within the motor cortex. Overall, previous research has provided supporting evidence for the view that $GABA_B$ mediated inhibition in the motor cortex declines with advancing age.

Although, there is evidence that the GABA-ergic mediated intracortical inhibition investigated using both SICI and SP play a crucial role in motor performance (Classen, Liepert, Wise, Hallett, & Cohen, 1998; Garry, Kamen, & Nordstrom, 2004), the extent to which and how these changes to cortical inhibitory processes influence motor performance

in older adults is not known.

6.4 Intracortical Inhibition and Interlimb Coordination

As mentioned in Chapter 2.1, upper- and lower-limb coordination performance of the non-isodirectional pattern with limbs on the same side of the body (ipsilateral) is more difficult than with limbs on opposite sides of the body (contralateral) (Hiraga et al., 2004, 2005; Meesen et al., 2006). The difficulty with the ipsilateral non-isodirectional pattern is even more pronounced in older adults (Serrien et al., 2000). One possible mechanism underlying the preferential limb combination for interlimb coordination at the cortical level may be related to the notion of 'functional cerebral space' (Kinsbourne & Hicks, 1978). It has been suggested that functional proximity between areas of the cerebral cortex influences the potential for interactions. That is, the difficulty in performing the non-isodirectional pattern using ipsilateral limbs is possibly a reflection of the functional proximity of limbs on the same side of the body, which may have higher interference at the cortical level compared to cortical representations of the muscles of the limbs on opposite sides of the body. As the cortical representation of muscles overlaps broadly (Schieber, 2001), and there is functional connectivity between representations within the motor cortex through extensive

intracortical afferents, it is likely that areas of hand and foot representation which are adjacent in the motor cortex interact during performance of interlimb coordination. Local connectivity between proximal brain regions in M1 may induce greater spread of activation from the increased level of drive required to execute an action (Carson & Kelso, 2004). Potentially this could cause interference with task performance of simultaneous non-isodirectional ipsilateral limbs movement since the representation of upper- and lower-limbs are in close proximity (Penfield & Rasmussen, 1950).

Until recently, there has been limited research using TMS to investigate the role of inhibitory processes in the control of interlimb coordination performance. Byblow et al. (2007) delivered paired-pulse TMS to M1 with the hand and arm resting in a prone position while subjects made phasic dorsiflexion or plantarflexion movements of the ipsilateral foot in time with a metronome. Short-interval intracortical inhibition (SICI) was selectively reduced in the right extensor carpi radialis (ECR) during dorsiflexion compared to plantarflexion of the right foot. Byblow et al. concluded that lower M1 inhibition during dorsiflexion would facilitate isodirectional movements when both the hand and foot were moved together. A similar reduction of ICI in hand muscles from both discrete and phasic dorsiflexion movements of the ipsilateral foot was reported using the silent period TMS

protocol (Sohn, Kang, & Hallett, 2005; Tazoe et al., 2007). Sohn et al. (2005) investigated intracortical inhibition of a hand muscle during movement of another body part. SP was obtained from the right abductor digiti minimi (ADM) muscle applying single pulse TMS with or without a ballistic right-foot movement. They found reduced SP duration when TMS was triggered by foot movement compared to without foot movement, indicating that cortical inhibition on the hand was released when the task required moving another part of the body. The authors concluded that changes in inhibitory processes may contribute to the performance of interlimb coordination tasks (Sohn et al., 2005). Tazoe and colleagues found a similar result employing phasic foot movements and measuring SPs from a hand muscle. Shortened SP was attributed to a decrease in intracortical inhibition caused by movement of the foot. Although in the above studies the influence of movements of the ipsilateral foot has been demonstrated on resting (Byblow et al., 2007) or isometrically contracted (Sohn et al., 2005; Tazoe et al., 2007) hand muscles, these studies suggest that intracortical inhibitory process may be important for the coordination of phasic movements involving both hand and foot. The aim of the present study, therefore, was to examine the role of intracortical inhibition in the regulation of interlimb coordination during the active coordination of upper- and lower-limbs.

6.5 Summary

It has been suggested that age-related changes in inhibitory control of executive function is responsible for degraded performance in cognitive tasks. However, the direct involvement of inhibitory processes at the neurophysiological level in task performance is not clear. Some studies suggest that cortical and/or corticospinal inhibition may be involved in the regulation of interlimb coordination. A question of importance is the extent to which the observed age-related decline in interlimb coordination is due to compromised control of cortical inhibition with advancing age. To our knowledge, only a few studies have previously used TMS to examine the neural mechanisms operating during inter-limb coordination in older adults (Sale & Semmler, 2005) and none have examined inhibitory processes during the active coordination of hand and foot movements. Identifying the neurophysiological mechanisms underlying the decline in interlimb coordination in older adults would provide a significant contribution to the understanding of age-related changes in motor function.

The following chapter (Chapter 7) includes the study which has been accepted by the journal Brain Research and is currently in press.

Chapter 7 Experimental Study 3

7.1 Introduction

Decreased interlimb coordination performance with advancing age is particularly evident in the non-isodirectional coordination of ipsilateral limbs. It has been suggested that older adults have increased difficulty suppressing the preferred isodirectional movement pattern (Greene & Williams, 1996; Heuninckx et al., 2004; Serrien et al., 2000). It has been argued that, as it is necessary to inhibit conflicting neural outputs (that tend to promote isodirectional patterns) in order to successfully perform the non-isodirectional pattern (Baldissera & Esposti, 2005; Borroni, Cerri, & Baldissera, 2004), an age-related decline of inhibitory control may be responsible for the reduced performance in older adults (Mattay et al., 2002; Spirduso & Choi, 1993).

At the molecular level, neuronal inhibition is mediated by GABA-ergic activity. Recent findings suggest that transcranial magnetic stimulation (TMS) can be used to assess inhibitory processes in the control of interlimb coordination performance (Byblow et al., 2007; Sohn et al., 2005; Tazoe et al., 2007). Both single and double-pulse TMS paradigms have been applied to study the effects of spatial constraints in hand-foot coordination on inhibition control in humans (Byblow et al., 2007; Sohn et al., 2005; Tazoe et al., 2007). In

these studies, the influence of movements of the ipsilateral foot was observed on resting or isometrically contracted hand muscles. Although a number of studies have examined excitability at the spinal level (Brooke et al., 1997; Hiraoka & Iwata, 2006; Knikou, 2007; Loadman & Zehr, 2007; Zehr, Collins, Frigon, & Hoogenboom, 2003), to our knowledge the role of cortical inhibitory processes in coordination patterns involving concurrent movements of ipsilateral or contralateral limbs has not been previously investigated.

There is increasing evidence that, in general, inhibition at both cortical (Eisen et al., 1996; Oliviero et al., 2006; Prout & Eisen, 1994; Sale & Semmler, 2005) and spinal levels (Kido, Tanaka, & Stein, 2004) decreases with advancing age. A question of importance, therefore, is the extent to which the greater difficulty observed in the performance of interlimb movements by older adults, particularly those involving non-isodirectional movements and ipsilateral limbs, are a consequence of reduced inhibitory processes in the aged. This question is addressed in the current study by exploring the effect of spatial constraints on inhibitory interactions between lower and upper-limb musculature. As aiming to measure intracortical inhibition in hand musculature actively engaged in coordinating movements with the foot, the length of the EMG silent period following a TMS pulse was the appropriate technique in this context. In addition to measuring SP

duration during phasic contraction of the hand, SPs when the hand was tonically contracted were also evaluated to allow comparison with previous studies showing modulation of ICI by movement of the foot (Byblow et al., 2007; Sohn et al., 2005; Tazoe et al., 2007).

While there is a large body of evidence to suggest that performance of non-isodirectional movements with the ipsilateral hand and foot is demanding for the elderly (Heuninckx et al., 2004), performing contralateral non-isodirectional movements with the same effectors seems to be rather easy. It is therefore hypothesized that the inhibitory processes involved in the control of iso-and non-isodirectional movements with contralateral hand and foot may differ to those involved during ipsilateral movements. As such, the comparison between contralateral and ipsilateral hand-foot coordination in younger and older adults may provide valuable information concerning the effect of aging on inter-hemispheric connectivity, as the elderly appear to recruit a more dispersed network of brain activity during interlimb coordination compared to the young (Heuninckx et al., 2005).

7.2 Methods

7.2.1 Participants

Thirty healthy volunteers (28 right-handed and 2 left-handed) volunteers participated in

the study, including 15 older adults (9 females, mean age 66.7 years, range 61-75 years) and 15 younger adults (9 females, mean age 21.9 years, range 18-33 years). All participants completed a brief medical questionnaire to ensure that inclusion criteria for the study were met. The Edinburgh handedness questionnaire (Oldfield, 1971) revealed that there was one left-handed participant in each group. Mini-Mental State Examination (Dick et al., 1984) was used to screen for cognitive deficits in the sample of older adults. The average score of participants in the current study was $M = 29.20$ ($SEM = 0.18$). Thus, all participants scored within the normal range (score ≥ 26) and were free of neurological impairment, symptomatic cardiovascular disease, diabetes and hypertension Written informed consent was obtained prior to participation in the study. Ethics approval for the study was obtained from the Human Research Ethics Committee (Tas) Network.

7.2.2 Apparatus

Participants were seated in a custom-made chair consisting of a steel frame with a wooden back support and padded seat. The chair had four aluminium levers that supported the limbs and enabled the hand and foot to make extension-flexion and dorsiflexion-plantarflexion movements, respectively. The right-hand and foot were firmly strapped to the levers with surgical tape. Limb position data were obtained using high-precision shaft

encoders (Penny and Gilles, SRH280) coaxial with each lever's axis of rotation. The voltage output from the shaft encoders was sampled at 2000 Hz using a 16-bit A/D system and was recorded on a computer hard drive for analysis off-line. The raw position data were low-pass filtered with a cutoff frequency of 10 Hz using a dual-pass Butterworth filter. Single-pulse TMS was applied using a flat circular coil (9 cm diameter) connected to a Magstim 200 (Magstim, Dyfed, UK). The coil was held tangentially over the scalp to induce a posterior-anterior current flow and to optimally elicit motor evoked potentials (MEPs) in the right extensor carpi radialis (ECR) muscle. Sampled (2000 Hz) EMG signals from the ECR through surface Ag/AgCl electrodes were amplified (1000X) and band-pass filtered (10 – 500 Hz) prior to sampling using a 16-bit AD system and recorded on a computer hard drive for analysis off-line. The individual resting motor threshold (rMT) was determined as the lowest stimulus intensity that produced MEPs of greater than 50 μV in at least three out of five consecutive trials. During experimental trials TMS was delivered at a stimulus intensity of 140 % of rMT (Sohn et al., 2005).

7.2.3 Procedure

As shown in Figure 7.1, there were two modes of wrist muscle activation involving either phasic or tonic contractions of the ECR. The phasic contraction conditions (Fig.

7.1A) required the cyclical coordination of either contralateral limbs (right hand and left foot) or ipsilateral limbs (right hand and right foot) using isodirectional (wrist extends while foot dorsiflexes and vice versa) or non-isodirectional movements (wrist extends while foot plantarflexes and vice versa) performed in a 1:1 frequency ratio. In the tonic contraction conditions (Fig. 7.1B) participants maintained an isometric extension of the right wrist against a strap with the wrist in approximately 9° of flexion while performing continuous dorsiflexion-plantarflexion movements with either their right or left foot. There were two tonic conditions with TMS being triggered either during the plantarflexion (PF) or foot dorsiflexion (DF) phase of the cyclical foot movements. Two baseline "hand only" conditions were also included in which either isometric or phasic contractions of the ECR were performed while the foot remained quiescent.

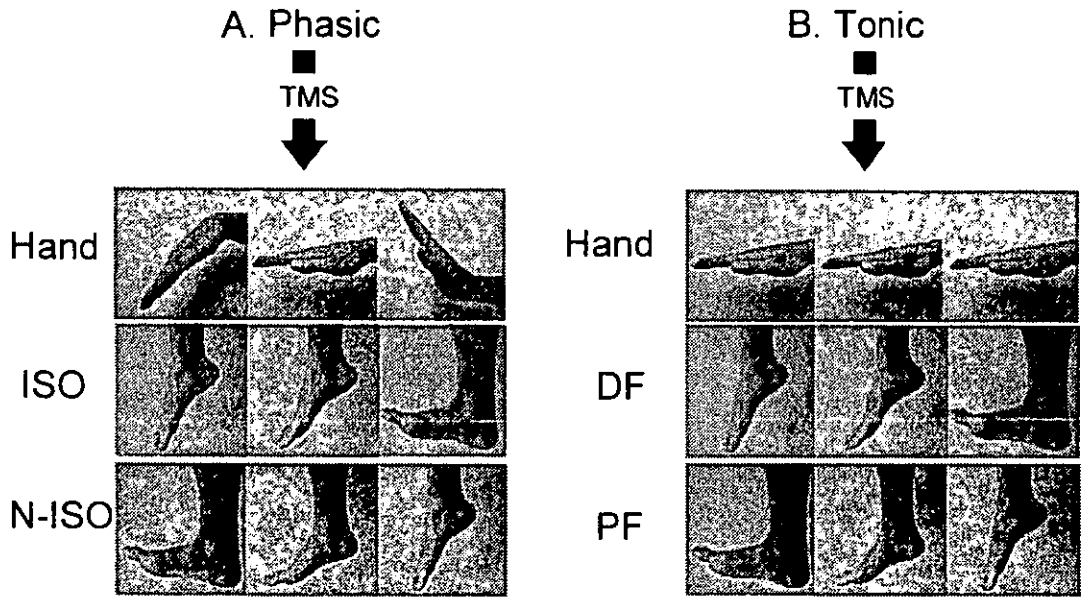


Figure 7.1 The timing of the TMS delivery relative to the hand and foot positions. **A.** *Phasic conditions*. Cyclical coordination of the hand and foot according to the isodirectional mode (*ISO*: both limb segments are moved in the same direction) and the non-isodirectional mode (*N-ISO*: both segments are moved in opposite directions). **B.** *Tonic conditions*. Hand was tonically contracted with foot dorsiflexion (*DF*) or plantarflexion (*PF*). Arrows indicate the timing of the TMS delivery relative to the hand and foot positions.

There were 2 trials in each phasic contraction condition (hand only, contralateral isodirectional, ipsilateral isodirectional, contralateral non-isodirectional, ipsilateral non-isodirectional) and 2 trials in each tonic contraction condition (hand only, contralateral foot DF, ipsilateral foot DF, contralateral foot PF, ipsilateral foot PF) making a total of 20 trials. Each trial lasted 30 seconds and the order of conditions was randomized across participants. In trials involving cyclical movements of the hand, foot, or both hand and foot, participants

were instructed to synchronise their movements with an auditory metronome set at 1 Hz. As the main aim of the study was to investigate cortical activity during interlimb coordination performed in the most natural manner, target movement amplitude was not required to avoid imposing an additional attentional load on participants, particularly older adults. There is evidence that the coordination of arm and leg movements requires greater central cost in the aged (Heuninckx et al., 2005; Sparrow et al., 2005). At least one familiarization trial was given before each condition. In the phasic and tonic conditions TMS was triggered by the foot movement and 5-6 TMS stimuli were delivered per trial with at least two cycles between consecutive phases. For the isodirectional phasic and DF tonic conditions, TMS was triggered when the foot reached 9° plantarflexion (relative to horizontal 0° plane) during the dorsiflexion phase. For the non-isodirectional phasic and PF tonic conditions, TMS was delivered when the foot reached 9° dorsiflexion during the plantarflexion phase. These procedures were used to deliver TMS during EMG activity of the ECR. For the phasic hand only condition, TMS was delivered when the hand reached the 9° flexion position during the extension phase, while for the hand only trials in the tonic condition TMS was delivered randomly with at least 5 s between pulses. Figure 7.2 illustrates typical EMG recordings of the silent period following a TMS pulse during phasic and tonic

contraction conditions.

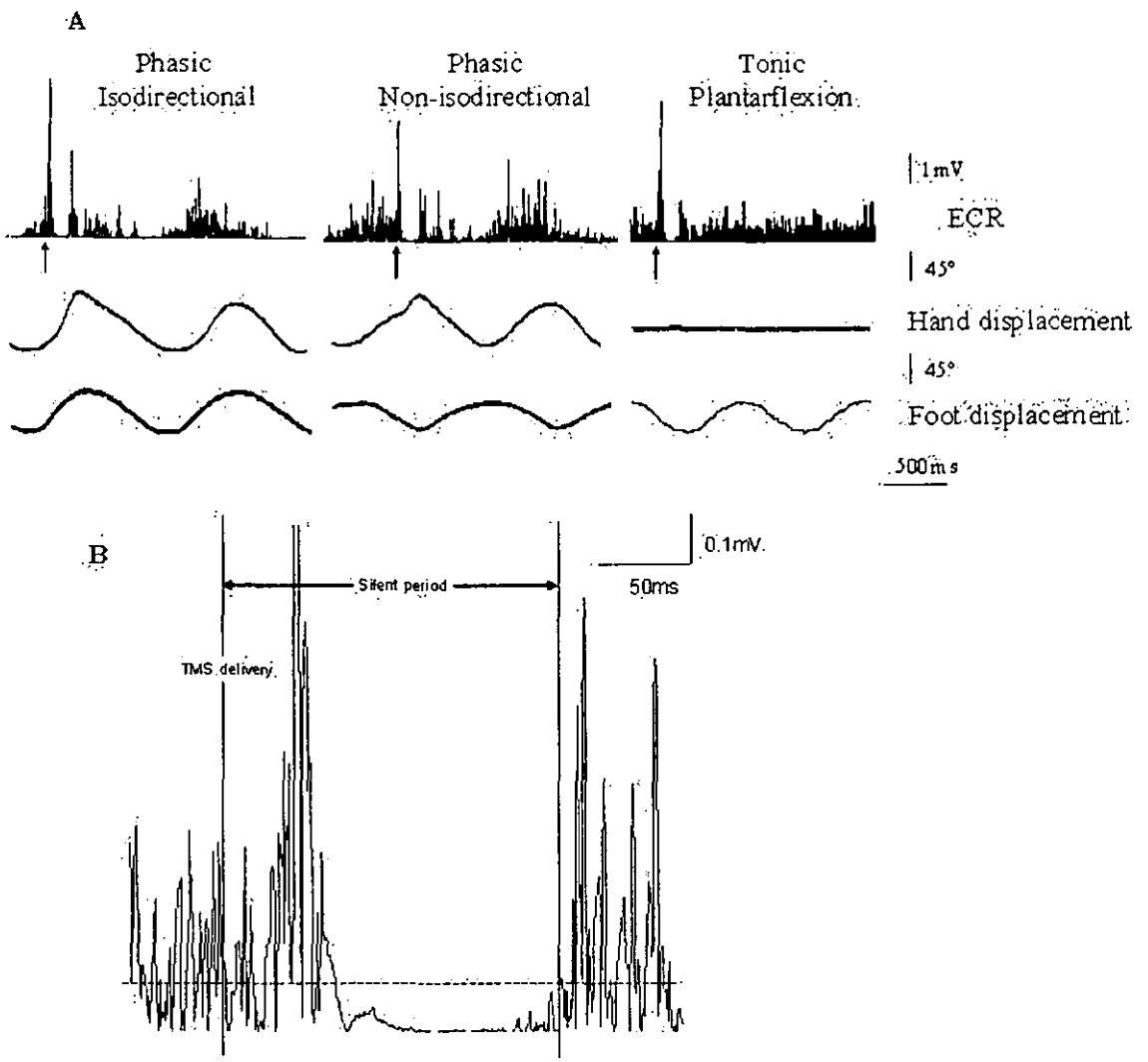


Figure 7.2 EMG recordings of the silent period following a TMS pulse during phasic and tonic contraction conditions. A. EMG activity in the ECR and hand and foot displacements for a single participant during the phasic isodirectional and non-isodirectional movement conditions, and the tonic plantarflex condition. The arrows indicate the time of TMS delivery in each condition. B. Silent period (SP) duration was measured from the time of TMS delivery to the reoccurrence of continuous EMG activity (horizontal dashed line: 1SD of the RMS of prestimulus EMG activity).

7.2.4 Data Analysis and Measures

Relative phase measures. The coordination between limb segments was assessed by a measure of relative phase obtained using the following procedure (Garry, van Steenis, & Summers, 2005). Each half-cycle (peak-to-valley, valley-to-peak) was rescaled to the range [1, −1]. This procedure results in a transformed displacement time-series approximating a cosine function. Continuous phase-angles (degree) for each limb were obtained by taking the arccosine of each point on the scaled time series; continuous relative phase was then simply the arithmetic difference of the phase-angles of the two limbs at each point. Circular statistics (Mardia, 1972) were utilized to calculate mean relative phase and standard deviation (SD) of relative phase. Absolute Error (AE) of relative phase provided a measure of accuracy of the relative phase as the average absolute deviation from mean target relative phase (0° for isodirectional mode, 180° for non-isodirectional mode), while standard deviation (SD) of relative phase provided a measure of pattern stability.

Spatiotemporal measures. Mean amplitude and standard deviation of limb movements were obtained by averaging the peak-to-peak amplitude of each cycle across the whole trial. The frequency of individual cycles (peak-to-peak) was calculated and the individual frequencies averaged to obtain mean movement frequency. The standard deviation of the movement

frequency produced by participants across trials was used as a measure of the temporal consistency. As the delivery of TMS may disrupt ongoing motor activity, the two cycles immediately after delivery of a TMS pulse were not included in the analyses of relative phase and spatiotemporal measures.

Hand position at TMS delivery. As TMS to the ECR was triggered by foot position, the hand position at TMS delivery was compared between groups and across conditions. The horizontal position of the hand was designated 0 deg and hand position was expressed as ± deviations from the horizontal. The standard deviation of the hand position was obtained as a measure the variability of the hand position at the time of TMS delivery.

Prestimulus EMG. The root mean square (RMS) scores of EMG activity recorded during the 50 ms prior to each TMS were calculated for each trial to compare the level of prestimulus EMG activity across conditions.

TMS measures. The amplitude of the MEP was measured peak-to-peak. The duration of the silent period was defined as the time between TMS delivery and the reoccurrence of continuous EMG activity. This was determined by calculating the RMS of the prestimulus EMG activity (100 ms preceding TMS delivery) and identifying the point at which post-stimulus EMG activity first exceeded 1 *SD* of this level as the end of the silent period

(Adapted from Tazoe et al., 2007).

7.2.5 Statistical Analysis

The data were examined using repeated measures ANOVAs with Huynh-Feldt epsilon corrections applied where necessary. Tukey HSD was used for post-hoc analyses as necessary. Cohen's d and partial η^2 (ηp^2) values were provided as a measure of effect size for *t*-tests and *F*-tests, respectively. For Cohen's *d* an effect size of 0.20 is considered small, 0.50 medium and 0.80 large, while 0.01 is considered small, 0.06 medium and 0.14 and higher large for ηp^2 (Stink & Stroh, 2006). The level of significance for all tests was set at $p < 0.05$. For the kinematic analyses of phasic contraction conditions, the amplitude and frequency of hand and foot movements were analyzed using repeated-measures ANOVAs with the between-factor GROUP (younger, older) and the within-factors LIMB (hand, foot), LIMB COMBINATION (ipsilateral, contralateral) and COORDINATION MODE (isodirectional, non-isodirectional). For the tonic contraction conditions, the amplitude and frequency of foot movements were analyzed using between age group ANOVAs with repeated-measures factors of LIMB COMBINATION and DIRECTION (dorsiflexion, plantarflexion).

The spatiotemporal measures of hand-foot coordination in the phasic contraction conditions, absolute error of relative phase and SD of relative phase, were examined by between age group ANOVAs with repeated-measures factors of limb combination and coordination mode. Statistical analysis of prestimulus EMG consisted of repeated measures ANOVA with the between-factor group and the within-factors of HAND ACTIVATION (HA: phasic, tonic) and CONDITION (hand only, contralateral isodirectional/DF; ipsilateral isodirectional/DF, contralateral non-isodirectional/ PF, ipsilateral non-isodirectional/PF). Due to differences in EMG level, separate 2 x 5 (GROUP) x (CONDITION) ANOVAs were conducted on TMS measures (MEP amplitude, and silent period duration (SP)) for the phasic and tonic contraction and hand position measures at the time of TMS delivery (relative hand position, SD of hand position) for the phasic contraction conditions. When comparisons between pairs of measures were required, paired t-tests were used. As our primary interest was on age-related differences in interlimb coordination, only main effects and interactions involving group as a factor will be reported. In all figures error bars are presented as standard error of the mean (SEM). STATISTICA 7.1 software (StatSoft, Inc., OK, USA) was used for statistical analysis.

7.3 Results

As age-related changes in interlimb coordination and TMS measures were of primary interest in the present study all main effects and only interactions involving GROUP are reported. Results of all statistical analyses are presented in Appendix F (in the attached CD).

7.3.1 Kinematic measures

Movement frequency. Analysis of movement frequency in the phasic activation conditions revealed significant main effects for LIMB, $F(1, 28) = 10.45$, $p = .003$, $\eta p^2 = 0.27$. Hand movements ($M = 0.96$ Hz, $SEM = 0.01$ Hz) were made at a slightly slower frequency than foot movements ($M = 0.97$ Hz, $SEM = 0.01$ Hz). Main effects of COORDINATION MODE, $F(1, 28) = 7.58$, $p = .010$, $\eta p^2 = 0.21$ and LIMB COMBINATION, $F(1, 28) = 7.34$, $p = .011$, $\eta p^2 = 0.21$ revealed that the isodirectional pattern ($M = 1.00$ Hz, $SEM = 0.003$ Hz) was executed at a higher frequency than the non-isodirectional pattern ($M = 0.93$ Hz, $SEM = 0.02$ Hz) and movements involving contralateral limbs ($M = 0.99$ Hz, $SEM = 0.01$ Hz) were performed at a higher frequency than movements of ipsilateral limbs ($M = 0.95$ Hz, $SEM = 0.01$ Hz). There was a significant main effect of GROUP, $F(1, 28) = 6.35$, $p = .018$,

$\eta p^2 = 0.18$, and significant interaction between GROUP and COORDINATION MODE, F (1, 28) = 7.23, $p = .012$, $\eta p^2 = 0.21$. Group was also involved in a significant GROUP x LIMB x COORDINATION MODE interaction F (1, 28) = 4.20, $p = .050$, $\eta p^2 = 0.13$, and a significant GROUP x LIMB COMBINATION x COORDINATION MODE interaction F (1, 28) = 4.34, $p = .046$, $\eta p^2 = 0.13$. These interactions, however, were qualified by an interaction of GROUP x LIMB x LIMB COMBINATION x COORDINATION MODE, F (1, 28) = 4.37, $p = .045$, $\eta p^2 = 0.13$. The four-way interaction, shown in Figure 7.3, indicated that younger adults were able to accurately maintain the target frequency with both hand and foot movements across all conditions. Older adults also accurately produced the required frequency when either contralateral or ipsilateral limbs moved in the same direction (isodirectional). However, when the limbs were required to move in opposite directions (non-isodirectional) older subjects moved slower than the target frequency, particularly when performing the ipsilateral limb combination. In the latter condition hand movements were performed at a significantly lower frequency than foot movements. Analysis of the frequency with which the foot was moved in the tonic activation conditions did not reveal any significant main effects or interactions ($ps > .115$).

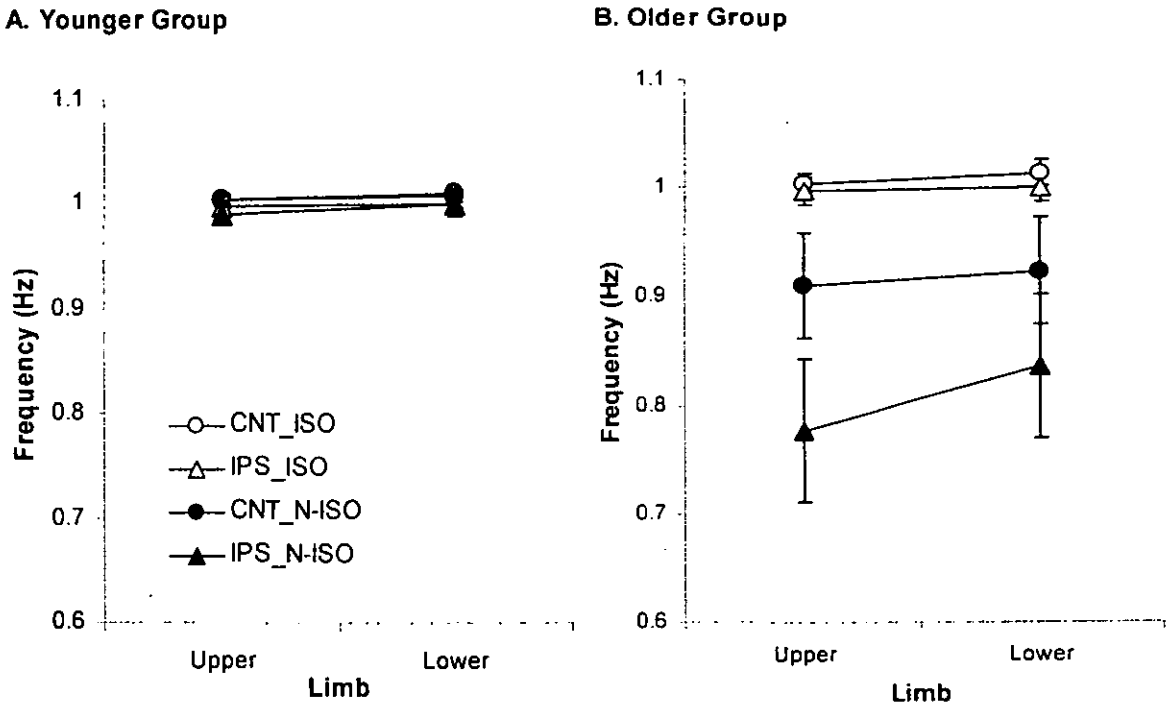


Figure 7.3 Mean movement frequency for A. Younger and B. Older group as a function of limb combination (CNT, contralateral; IPS, ipsilateral) and coordination mode (ISO, isodirectional; N-ISO, non-isodirectional).

Variability of Frequency. There were significant main effects of LIMB, $F(1, 28) = 10.21$, $p = .003$, $\eta p^2 = 0.27$, and LIMB COMBINATION, $F(1, 28) = 4.43$, $p = .044$, $\eta p^2 = 0.14$. These main effects suggested that movement frequency of the lower-limb was performed with a larger variability ($M = 0.108$ Hz, $SEM = 0.005$ Hz) than frequency of upper-limb ($M = 0.091$ Hz, $SEM = 0.002$ Hz), and frequency was more variable when ipsilateral limbs were coordinated ($M = 0.106$ Hz, $SEM = 0.005$ Hz) than contralateral limbs ($M = 0.093$ Hz, $SEM = 0.003$ Hz).

Analysis of the SD of frequency for the tonic conditions showed a significant main

effect of DIRECTION, F (1, 28) = 5.55, p = .026, ηp^2= 0.17, indicating that the frequency of foot movements was more variable in the PF (M = 0.113 Hz, SEM = 0.005 Hz) than DF (M = 0.097 Hz, SEM = 0.004 Hz) condition.

Amplitude. Analysis of mean amplitude revealed significant main effects of LIMB, F (1, 28) = 225.04, p = .001, ηp^2= 0.89, COORDINATION MODE, F (1, 28) = 40.75, p = .001, ηp^2= 0.59, and LIMB COMBINATION, F (1, 28) = 20.49, p = .001, ηp^2= 0.42. The mean amplitude of hand movements (M = 97.23°, SEM = 2.28°) was larger than foot movements (M = 50.96°, SEM = 0.77°); movement amplitude was larger during performance of the non-isodirectional coordination mode (M = 79.69°, SEM = 2.91°) than the isodirectional mode (M = 68.51°, SEM = 2.41°), and larger amplitudes were evident when ipsilateral limbs (M = 76.06°, SEM = 2.79°) were coordinated than contralateral limbs (M = 72.14°, SEM = 2.64°). There was a main effect for GROUP, F (1, 28) = 5.21, p = .030, ηp^2= 0.16, and interaction of GROUP and LIMB, F (1, 28) = 9.81, p = .004, ηp^2= 0.26. As illustrated in Figure 7.4, the two-way interaction revealed that although there were no differences in the amplitude of foot movements, older adults made significantly larger amplitude hand movements than younger adults. The amplitude of foot movements during the tonic

contraction conditions revealed no significant main effects or interactions (p >.063).

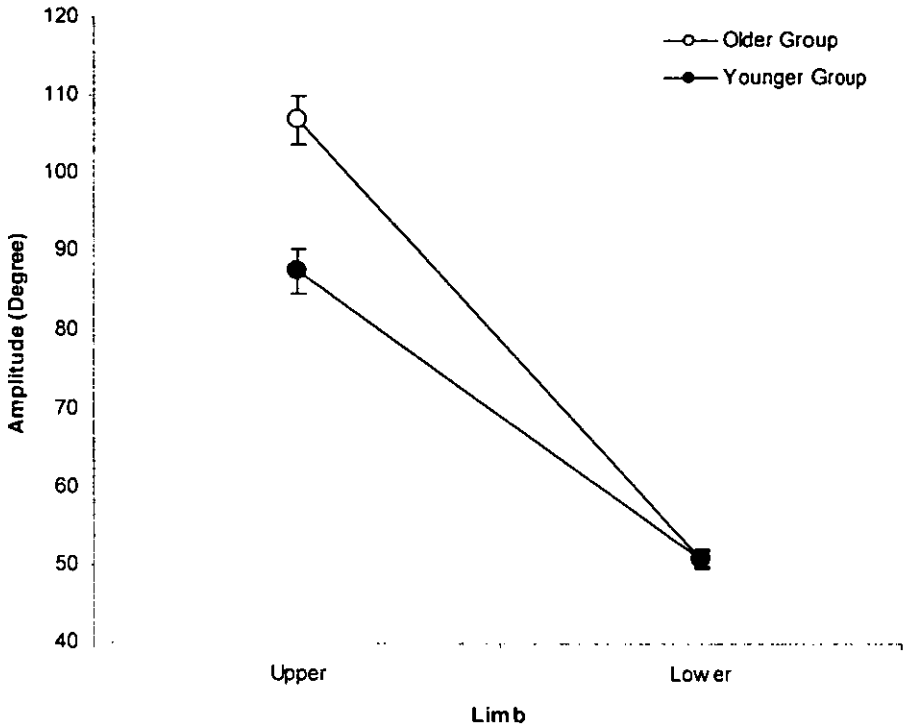


Figure 7.4 Mean movement amplitude of upper- and lower-limb for younger and older adults.

Variability of Amplitude. Analysis of the SD of amplitude for the phasic activation condition revealed that there were significant main effects of LIMB COMBINATION, F (1, 28) = 5.58, p = .025, ηp^2= 0.17, and COORDINATION MODE, F (1, 28) = 6.25, p = .018, ηp^2= 0.18. These results indicated that the amplitudes of ipsilateral limb movements (M = 7.66°, SEM = 0.79°) and non-isodirectional movements (M = 7.70°, SEM = 0.80°) were more variable than those involving contralateral limbs (M = 5.50°, SEM = 0.35°) and

isodirectional movements (M = 5.46°, SEM = 7.66°). Although there was a significant interaction of GROUP x LIMB, F (1, 28) = 4.39, p = .045, ηp^2= 0.14, post-hoc comparisons revealed non-meaningful differences. Therefore, the significant main effects of GROUP, F (1, 28) = 4.90, p < .001, ηp^2= 0.15, and LIMB, F (1, 28) = 54.95, p < .001, ηp^2= 0.66 were best interpreted separately. These main effects suggested that movement amplitude was more variable in the younger adults (M = 7.84°, SEM = 0.76°) than older adults (M = 5.33°, SEM = 0.42°) and upper-limb amplitude was more variable (M = 9.12°, SEM = 0.76°) than lower-limb amplitude (M = 4.04°, SEM = 0.29°). Analysis of the SD of amplitude for the tonic condition revealed that the amplitude of foot movements in older adults was less variable (M = 2.90°, SEM = 0.18°) than in the younger adults (M = 5.11°, SEM = 0.63°), F (1, 28) = 5.29, p = .029, ηp^2= 0.16.

7.3.2 Relative phase measures

Absolute Error (AE) of Relative Phase. Analysis of mean AE of relative phase for the phasic contraction conditions showed no significant main or interaction effects (p > .139).

Standard Deviation (SD) of Relative Phase. The ANOVA performed on the SD of relative phase revealed significant main effects of COORDINATION MODE, F (1, 28) = 20.97, p =

.001, $\eta p^2 = 0.43$, and LIMB COMBINATION, $F(1, 28) = 13.41$, $p = .001$, $\eta p^2 = 0.32$. The isodirectional coordination mode ($M = 22.96°$, $SEM = 0.64°$) and movements involving coordination of contralateral limbs ($M = 24.69°$, $SEM = 1.20°$) were performed with a higher degree of stability than the non-isodirectional coordination mode ($M = 30.55°$, $SEM = 1.77°$) and movements requiring the coordination of ipsilateral limbs ($M = 28.82°$, $SEM = 1.57°$). There was also a significant main effect of GROUP, $F(1, 28) = 10.90$, $p = .002$, $\eta p^2 = 0.28$, and an interaction of GROUP and COORDINATION MODE, $F(1, 28) = 7.79$, $p = .009$, $\eta p^2 = 0.22$ (Figure 7.5). There was no difference in variability of relative phase between younger and older adults during production of isodirectional patterns ($p = .82$), whereas older adults exhibited a higher degree of instability than younger adults when performing non-isodirectional patterns.

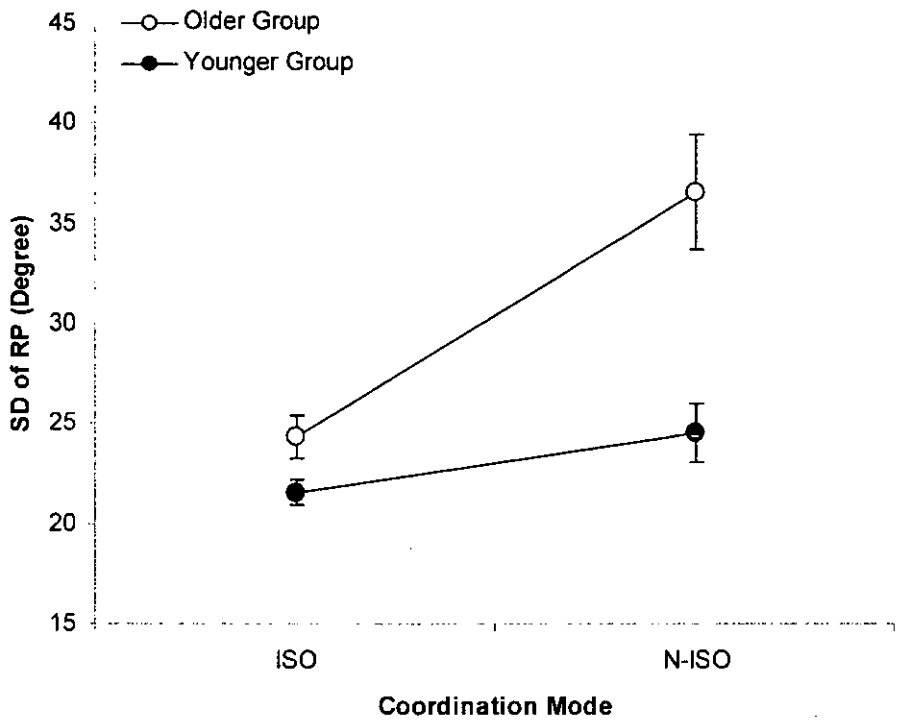


Figure 7.5 Standard deviation of relative phase for older and younger groups as a function of coordination mode (ISO, isodirectional; N-ISO, non-isodirectional).

The interaction of GROUP and LIMB COMBINATION did not reach conventional levels of significance, $F(1, 28) = 2.91$, $p = .099$, $\eta p^2 = 0.09$. However, because of its theoretical importance this trend was further investigated by examining the effect of LIMB COMBINATION for each age group separately. Specifically, in older adults the ipsilateral limb combination was significantly less stable ($M = 33.48°$, $SEM = 2.59°$) than the contralateral limb combination ($M = 27.42°$, $SEM = 2.15°$) ($p = .004$), whereas in younger adults the ipsilateral ($M = 24.16°$, $SEM = 1.32°$) and contralateral ($M = 21.95°$,

SEM = 0.85°) limb combinations did not differ (p = .52).

7.3.3 TMS data

Prestimulus EMG. A significant main effect of HA, F (1, 28) = 118.54, p < .001, ηp^2= 0.81, indicated that prestimulus EMG was higher during phasic activation (M = 0.133 mV, *SEM* = 0.006 mV) than tonic activation of the hand (M = 0.042 mV, *SEM* = 0.002 mV). There was also an interaction of HA and CONDITION, F (3.21, 89.96) = 9.41, p < .001, ηp^2= 0.25, showing that within the phasic activation conditions, prestimulus EMG was lower when performing the isodirectional pattern with either limb combination than the non-isodirectional pattern or the baseline hand only condition (See Figure 7.6). In contrast, EMG activity during tonic hand activation was consistent across the five conditions. Of particular importance for evaluation of age-related differences in TMS measures was that neither the main effect of GROUP nor any interactions involving GROUP were significant (Fs < 1.05, p > .38), indicating that the level of prestimulus muscle activity did not differ between younger and older adults across conditions.

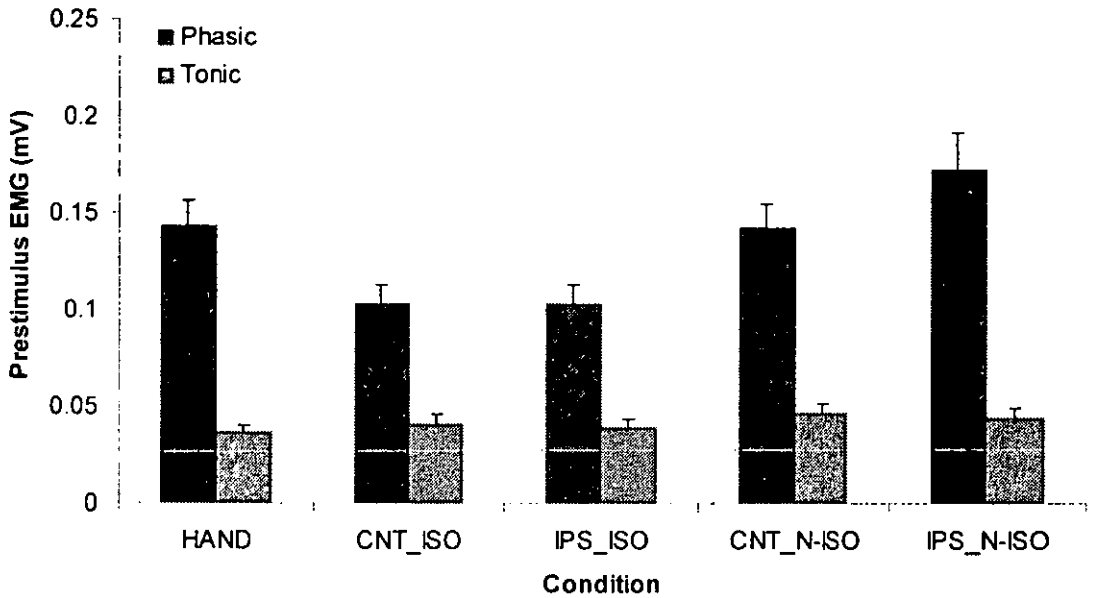


Figure 7.6 Prestimulus EMG across conditions. HAND = hand only; CNT_ISO = contralateral isodirectional; IPS_ISO = ipsilateral isodirectional; CNT_N-ISO = contralateral non-isodirectional; mode with contralateral limb combination; IPS_N-ISO = ipsilateral non-isodirectional.

Hand position at the time of TMS delivery. As the delivery of TMS to the ECR was triggered by foot position, it was important to determine if there were systematic differences in the hand position when TMS was delivered between groups and/or conditions. Although on average, TMS was delivered when the hand was slightly closer to the horizontal zero position in the movements produced by older participants (M = - 7.18°, SEM = 1.56°) than in the movements of the young group (M = -13.65°, SEM = 2.03°), neither the main effect of GROUP, F (1, 28) = 3.02, p = .09, ηp^2= 0.10, nor the GROUP x CONDITION interaction, F (2.68, 74.96) = 0.57, p = .69, ηp^2= 0.02, reached significance

(Figure 7.7). There was a main effect for CONDITION, F (2.68, 74.96) = 12.07, $p < .001$, $\eta p^2 = 0.30$. Post-hoc analysis showed that TMS was delivered closer to the horizontal zero position when non-isodirectional movements were made with contralateral (M = -6.24°, SEM = 2.41°) and ipsilateral (M = -1.71°, SEM = 2.34°) limbs than when isodirectional movements were performed (contralateral, M = -18.19°, SEM = 3.27°; ipsilateral, M = -17.90°, SEM = 3.70°).

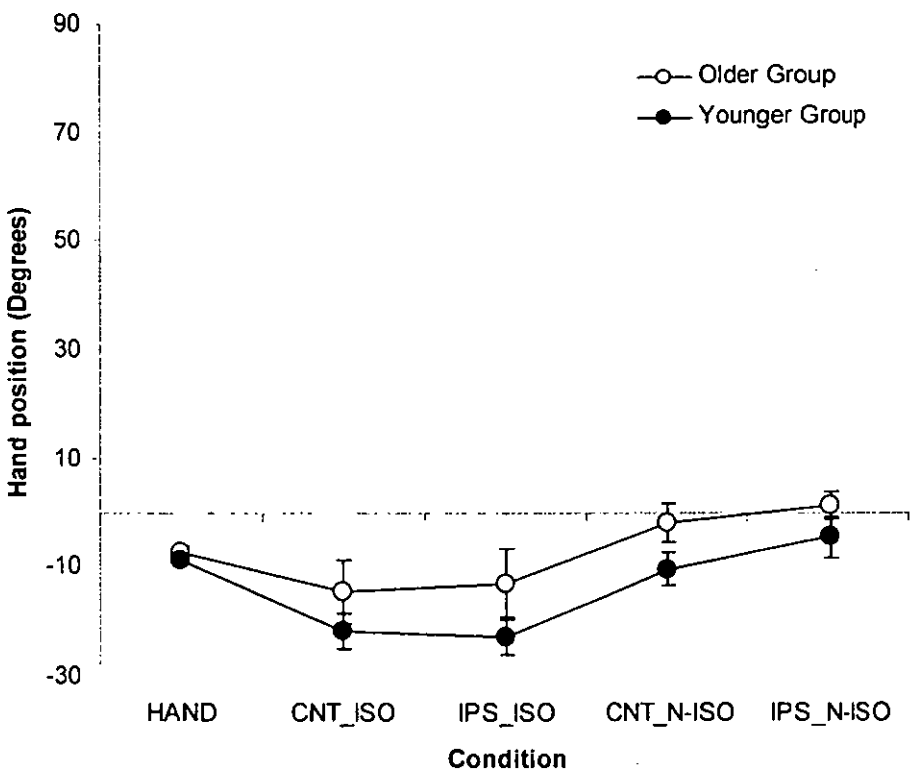


Figure 7.7 Mean hand position at the time of TMS *delivery* for older and younger groups. HAND = hand only; CNT_ISO = contralateral isodirectional; IPS_ISO = ipsilateral isodirectional; CNT_N-ISO = contralateral non-isodirectional; mode with contralateral limb combination; IPS_N-ISO = ipsilateral non-isodirectional.

Analysis of the variability of the hand position at the time of TMS delivery revealed that older adults exhibited greater variability (M = 7.41°, SEM = 0.71°) than young adults (M = 6.01°, SEM = 0.54°), but the main effect of GROUP was only marginally significant, F (1, 28) = 3.61, p = .07, ηp^2= 0.11. There was greater variability in the hand position at the time of TMS delivery during non-isodirectional (contralateral, M = 9.45°, SEM = 0.86°; ipsilateral, M = 10.56°, SEM = 1.12°) than isodirectional coordination modes (contralateral, M = 5.71°, SEM = 0.69°; ipsilateral, M = 6.79°, SEM = 0.76°), F (2.52, 70.65) = 21.98, p = .001, ηp^2= 0.44. Importantly, the GROUP x CONDITION interaction was not significant, F (2.52, 70.65) = 0.73, p = .57, ηp^2= 0.03 (Figure 7.8). Thus, as only a small difference in the hand position at TMS delivery was evident between older and young adults overall, comparing the two groups of participants on TMS measures was appropriate.

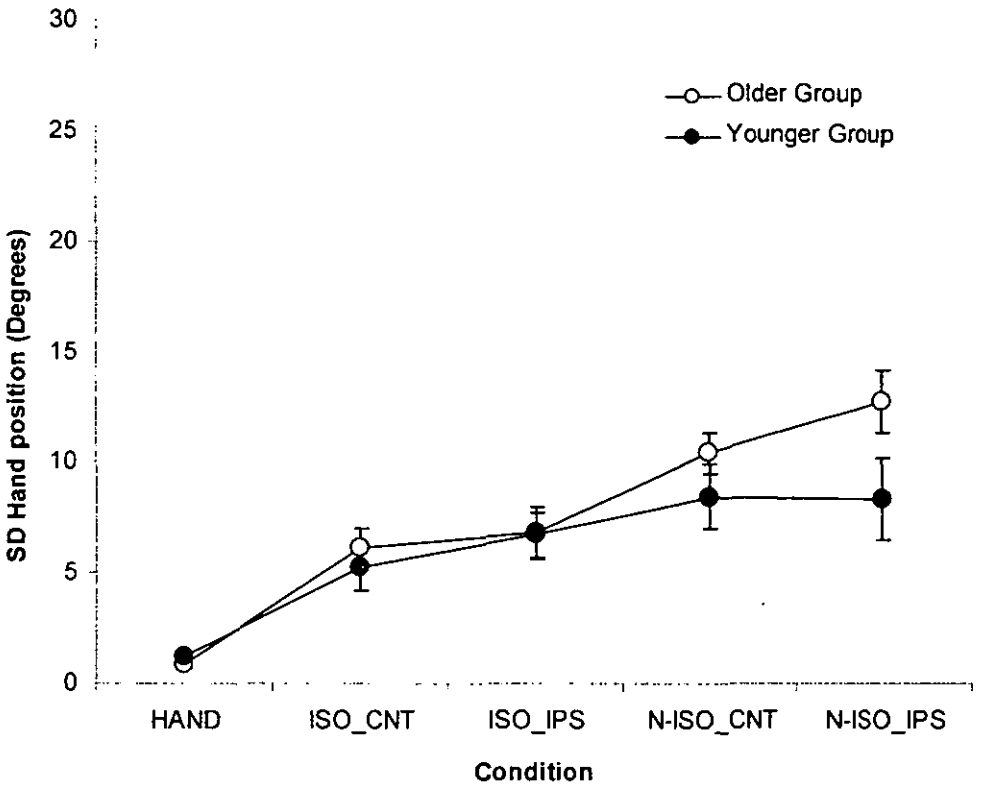


Figure 7.8 Standard deviation of hand position at the time of TMS delivery for older and younger groups. HAND = hand only; CNT_ISO = contralateral isodirectional; IPS_ISO = ipsilateral isodirectional; CNT_N-ISO = contralateral non-isodirectional; mode with contralateral limb combination; IPS_N-ISO = ipsilateral non-isodirectional.

MEP amplitude. The older group had a slightly higher rMT (41.33 %, *SEM* = 0.94 % stimulator output) than the younger group (*M* = 39.73 %, *SEM* = 1.12 %), but the difference was not statistically significant by an independent *t*-test, $t(28) = 1.13$, $p = .269$, $d = 0.44$. A comparison of mean MEP amplitude during phasic and tonic contraction conditions showed that MEPs were generally larger during phasic contraction (*M* = 1.50 mV, *SEM* = 0.04 mV) than tonic contraction conditions (*M* = 1.26 mV, *SEM* = 0.04 mV), $t(29) = 3.39$, $p = .002$, d

= 0.62 (Figure 7.9).

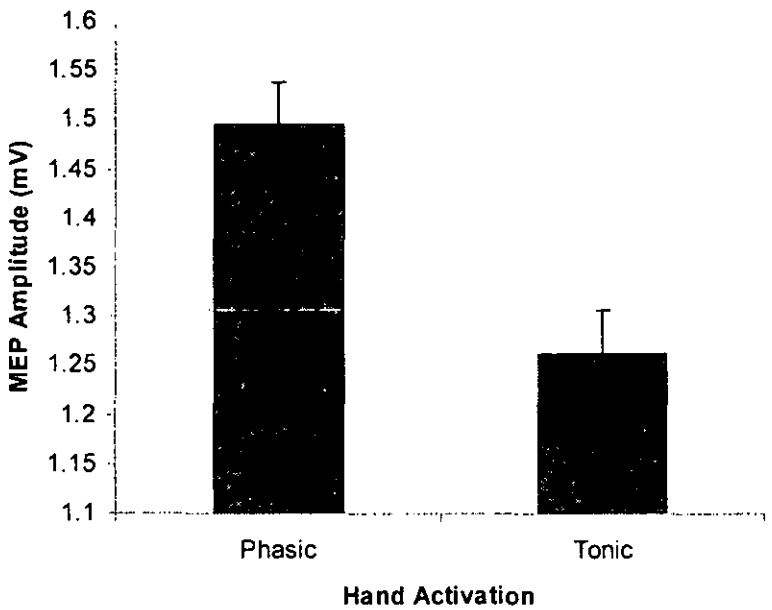


Figure 7.9 Mean MEP amplitude in phasic and tonic hand activation.

Analysis of MEP amplitude during the phasic contraction conditions revealed a significant main effect of GROUP, $F(1, 28) = 6.71$, $p = .015$, $\eta p^2 = 0.19$, with the younger adults exhibiting higher amplitudes ($M = 1.70$ mV, $SEM = 0.06$ mV) than the older adults ($M = 1.29$ mV, $SEM = 0.05$ mV). There were no effects of CONDITION or GROUP by CONDITION interaction. A similar analysis of MEP amplitude during tonic contraction conditions revealed no significant main or interaction effects ($p > .290$).

Silent period duration. In general, SP durations were longer during tonic contraction

conditions (M = 152.54 ms, SEM = 1.99 ms) than phasic contraction conditions (M = 138.27 ms, SEM = 2.51 ms), t (29) = 3.47, p = .002. Analysis of SP duration during phasic contraction conditions revealed a significant main effect of CONDITION, F (3.43, 96.17) = 4.01, p = .004, ηp^2= 0.13, and an interaction of GROUP and CONDITION, F (3.43, 96.17) = 4.43, p = .002, ηp^2= 0.14. As can be seen in Figure 7.10, younger adults showed a modulation of SP durations across conditions, whereas SP durations did not differ in older adults. Specifically, during phasic hand movement conditions younger adults evidenced significantly longer SP durations when non-isodirectional movements were performed with ipsilateral limbs (M = 148.42 ms, SEM = 7.33 ms) than during the hand only condition (M = 139.47 ms, SEM = 8.70 ms), and when contralateral limbs were coordinated in either the isodirectional (M = 130.93 ms, SEM = 8.08 ms) or non-isodirectional mode (M = 133.55 ms, SEM = 8.33 ms). The ipsilateral isodirectional condition (M = 144.18 ms, SEM = 7.35 ms) in the younger group also showed a significantly longer SP duration than the contralateral isodirectional condition, but did not differ from the hand only condition (p = .089). In contrast, there were no significant differences in SP durations among conditions in older adults (p > .10). A similar analysis of SP duration during tonic contraction conditions produced no significant main or interaction effects (p > .10).

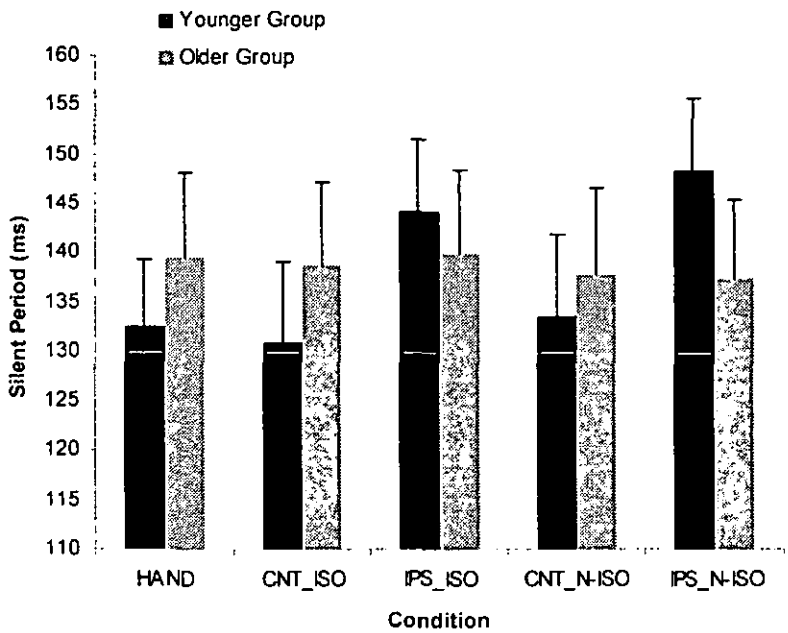


Figure 7.10 Mean silent period duration in phasic hand activation conditions for older and younger groups. HAND = hand only; CNT_ISO = contralateral isodirectional; IPS_ISO = ipsilateral isodirectional; CNT_N-ISO = contralateral non-isodirectional; mode with contralateral limb combination; IPS_N-ISO = ipsilateral non-isodirectional.

7.4 Discussion

The present study investigated age-related differences in cortical excitation and inhibition during interlimb coordination. Kinematic measures of performance revealed that younger adults were able to accurately perform isodirectional and non-isodirectional movement patterns with limbs on either the same side (ipsilateral) or opposite sides (contralateral) of the body. Older adults, in contrast, showed accurate performance of

contralateral limb patterns and the isodirectional pattern performed by ipsilateral limbs, but evidenced difficulty in coordinating non-isodirectional movements with the hand and foot on the same side of the body. When producing the non-isodirectional coordination mode, older adults made movements with ipsilateral limbs more slowly and with lower stability than movements with contralateral limbs. These results are in line with previous research showing reduced performance in non-isodirectional patterns, but preserved capability to perform isodirectional patterns in older adults (Greene & Williams, 1996; Heuninckx et al., 2005; Serrien et al., 2000).

Interestingly, there were no age differences in the accuracy with which the required relative phase between the limbs was produced. This may be partly due to the significant reduction in movement frequency by older adults in the most difficult ipsilateral non-isodirectional pattern. As discussed in Chapter 3, it has been argued that as the quality of afferent information from the limbs declines with age (Seidler & Stelmach, 1995). Therefore, older adults must monitor sensory feedback more carefully during a coordination task. Serrien et al. (2000) further suggest that processing the degraded sensory information requires extra cognitive load for older adults. Consequently, older adults show degraded performance of non-isodirectional coordination patterns that require more

conscious control and mental effort. Recent fMRI studies have shown higher activation in prefrontal regions in the elderly during the non-isodirection coordination mode consistent with the increased cognitive monitoring of performance (Heuninckx et al., 2005; Heuninckx et al., 2008).

Of particular importance in the present study were the age-related differences in cortical excitability and inhibitory processes observed during interlimb coordination. Consistent with previous studies, despite showing equivalent levels of prestimulus EMG activity, older adults showed lower motor cortex excitability than younger adults (Oliviero et al., 2006; Pitcher et al., 2003; Sale & Semmler, 2005). The reduced cortical excitability in the older group may reflect loss of motoneurons in the cortical and spinal system, altered balance between excitation and inhibition, or declined connectivity between motor commands and corticospinal system (Sale & Semmler, 2005). For both groups MEP amplitudes were significantly higher in conditions requiring phasic hand movements than in conditions in which the hand was tonically contracted. This difference in cortical excitability is likely a reflection of the higher level of prestimulus muscle activity evident during phasic movements of the hand (e.g., Hasegawa, Kasai, Tsuji, & Yahagi, 2001). Although the up-regulation of cortical excitability during the phasic activation conditions was less in older

adults, the concomitant release of inhibition evident during phasic compared to tonic activation of the ECR was similar for younger and older adults.

When the coordinated limbs (contralateral) involved different hemispheres, both groups showed no change in either MEP amplitude or SP duration compared to the baseline condition. Age-related differences were evident, however, in the modulation of inhibitory processes during coordination of limbs controlled by the same hemisphere. Specifically, young adults showed longer silent periods, reflecting increased inhibition, during coordination of ipsilateral limbs with the most difficult non-isodirectional pattern displaying significantly longer SP durations than coordination of contralateral limbs or hand only baseline conditions. Older adults, in contrast, did not modulate the level of inhibition across contralateral or ipsilateral limb conditions. One possible explanation of the lack of modulation in SP duration across conditions in older adults compared to young adults might be related to group differences in the position of the hand at the time of TMS delivery across movement conditions. As TMS delivery to the hand was triggered by foot position, it is possible that older adults were less able to maintain the correct phase between the hand and foot within and across trials and conditions. As cortical excitability is modulated as a function of movement phase during unimanual rhythmic movements

(Carson et al., 2004), then the lack of modulation of SP duration in older adults may have resulted from greater differences in the hand position at TMS delivery across conditions in older than young adults. This explanation seems unlikely because although there were significant differences in mean hand position and variability between isodirectional and non-isodirectional movements, irrespective of limb combination, both young and older adults showed the same pattern. Furthermore, young adults showed a significant increase in SP duration for isodirectional movements performed with ipsilateral limbs (144.18 ms) compared to contralateral limbs (130.93 ms), despite the hand being in similar positions when TMS was delivered (-21.81° and -22.66°, respectively). A similar pattern was evident for non-isodirectional movements. That is, a significant difference in SP duration but similar hand positions for the two limb combinations. Older adults also exhibited similar hand positions for isodirectional movements (- 2.04° and 1.22°) and non-isodirectional movements (-10.44° and -4.65°) performed by different limb combinations, but SP durations did not differ. It is likely, therefore, that the similarity of SP durations across conditions in older adults cannot be attributed to differences in hand positions at the time of TMS delivery between young and older adults. Rather, the lack of modulation may reflect a deficit in the ability to modulate inhibitory processes with aging. This is the first

demonstration of age-related differences in inhibition during the performance of patterns involving the coordination of contralateral or ipsilateral limbs.

Another possibility is that the observed SP duration differences in young adults reflected differing levels of background EMG activity across conditions. That is, the longer SP duration evident during non-isodirectional movements involving ipsilateral limbs was a consequence of higher background EMG activity in that condition. This explanation also seems unlikely as comparable SP durations were observed in conditions with different levels of background EMG, such as iso- and non-isodirectional movements performed with contralateral limbs. Furthermore, background EMG has been shown to have little effect on the duration of the SP (Terao & Ugawa, 2002). For example, Taylor and colleagues (Taylor, Allen, Butler, & Gandevia, 1997) examined the effect of stimulus intensity and background EMG on SP duration. A wide range of TMS intensities (80-140 % of active MT) was applied during voluntary contractions producing 0-75 % of maximal force (MVC) in biceps brachii, brachioradialis and adductor pollicis muscles. The duration of SP in all the muscles increased with stimulus intensity, but was comparable across levels of MVC. Similarly, Saisanen et al. (2008) also reported that the length of SP was independent from the level of muscle activation (20-80 % of MVC). These findings suggest that the differences in the

length of SP observed in the present study can be attributed to the experimental manipulations employed rather than to different levels of background EMG.

Previous studies of ipsilateral limb coordination in young adults have compared dorsiflexion and plantarflexion movements of the foot while the hand remained quiescent. In the present study the hand was actively contracting and it is likely that the interaction of movement related information from the hand and foot influenced the form of phase-dependent modulation of the SP duration in the ECR. The increase in SP duration observed during non-isodirectional ipsilateral limb coordination may reflect increased inhibition necessary in this condition to prevent regression to the more intrinsically stable isodirectional coordination mode (Baldissera et al., 1982; Heuninckx et al., 2005). There is evidence of interactions within the motor cortex facilitating isodirectional coupling between ipsilateral hand and foot areas through subliminal postural co-activations of the hand when only the foot is moved (e.g., Baldissera & Esposti, 2005; Borroni et al., 2004). Thus, non-isodirectional coordination of ipsilateral limbs would require the suppression of intracortical connections favouring isodirectional coupling between hand and foot areas. The lack of elevation in the level of inhibition in older adults during the performance of the non-isodirectional ipsilateral limb coordination may underlie their poorer performance of

this pattern. In addition to interactions within the motor cortex, it is also possible that other areas of brain such as secondary motor areas contribute to the directional organisation of interlimb coordination. Recently, Byblow et al. (2007), using a paired-pulse TMS protocol, suggested that dorsal premotor cortex (PMd) was possibly involved in the regulation of directional coupling between upper and lower limbs. An involvement of PMd in directional control of hand and foot coordination is also consistent with previous fMRI studies by Heuninckx and colleagues (2005; 2008). Progressive degeneration related to PMd due to aging may also be associated with poor performance of the non-isodirectional ipsilateral limb coordination in older adults. Likewise, degeneration at the motor neuron/segmental level with aging may have contributed to lack of modulation of inhibition in the older group.

It is interesting to note that young adults showed a non-significant increase in inhibition in the active ECR, relative to the hand only baseline condition, during isodirectional coordination of ipsilateral limbs. One possibility is that the observed pattern may reflect postural instabilities induced when the two limbs on the same side of the body are moved simultaneously. Recently, Baldissera and colleagues (Baldissera, Rota, & Esposti, 2008) have demonstrated anticipatory postural adjustments (APAs) in the

contralateral limb accompanying unidirectional and cyclical arm movements. Furthermore, contralateral APAs are positively related to size of the possible displacement of the centre of mass induced by the primary movement(s). As such, making coupled isodirectional movements of the ipsilateral hand and foot would produce significantly greater postural imbalance than movement of a single limb or when limbs on opposite sides of the body are moved isodirectionally together. It is also suggested that to execute coupled movements of ipsilateral limbs, contralateral APAs must be actively suppressed (Baldissera et al., 2008). Accordingly, the increased SP duration evident during the isodirectional coordination of ipsilateral compared to contralateral limbs in this study may be related to overcoming the influence of automatic posture preserving mechanisms.

The increased level of inhibition exhibited by the younger group during ipsilateral limb coordination, however, seemed to be beneficial only for the performance of the non-isodirectional pattern, as the isodirectional pattern was performed equally well by young and older adults. This may be related to the fact that as isodirectional patterns are inherently stable regardless of limb combination (Baldissera et al., 1982; Kelso & Jeka, 1992; Serrien & Swinnen, 1997; Swinnen et al., 1995; Wenderoth et al., 2004), the benefit of elevated cortical inhibition during coordination of ipsilateral limbs was not evident in performance

during the isodirectional coordination mode. While the increased inhibition during ipsilateral isodirectional coordination did not appear to be associated with superior performance in this condition for younger adults, it is possible that it would be associated with age-related differences in pattern maintenance at higher frequency levels as the size of APAs appear to increase with increases in movement frequency (Shiratori & Aruin, 2007). There is some evidence that older adults exhibit difficulties performing ipsilateral isodirectional coordination at cycling frequencies above 1.50 Hz (Heuninckx et al., 2004).

In conclusion, the current study suggests that the process of aging induces changes to cortical excitatory and inhibitory function during interlimb coordination. A significant finding was a difference in inhibitory control between young and older adults when performing movements with either contralateral or ipsilateral limbs, with older adults exhibiting a reduced ability to increase inhibitory function during coordination of ipsilateral limbs. An age-related decline in the ability to modulate activity in appropriate motor networks when required has also been linked recently to deficits in force production (Ward, Swayne, & Newton, 2008) and practice-dependent plasticity in older adults (Florian, Müller-Dahlhaus, Orekhov, Liu, & Ziemann, 2008). The present research suggests that the decreased ability to modulate inhibitory function may be related to age-related decreased

performance in tasks requiring the coordination of upper and lower limbs.

Chapter 8 Summary and Conclusion

8.1 Summary of the Present Research

The present research investigated age-related changes in interlimb coordination performance and associated cognitive and neural functions. The hypotheses that general slowing, decreased resource capacity, and reduced inhibitory processes are factors in age-related decline of movement performance were provided as a framework to investigate the nature of interlimb coordination in older adults.

Part 1 of the research examined the attentional cost of maintaining interlimb coordination patterns. Of particular interest were age differences when task difficulty was controlled between younger and older participants by individualising the frequency at which the tasks were performed. Previous research using the same movement frequency for younger and older adults often exaggerated age differences since cognitive, motor, neural, and perceptual processes slow down with age (e.g., Hunter et al., 2001; Morgan et al., 1994; Salthouse, 1991, 1996).

In the first study younger and older adults performed interlimb coordination tasks involving the coordination of an arm and a leg on either the same (ipsilateral) or opposite (contralateral) sides of the body while concurrently responding to probe stimuli. Consistent

with previous research (Heuninckx et al., 2004), coordination performance in older adults was reduced relative to younger adults especially in the situation where attentional requirements were high. In addition, analysis of EMG data indicated age-related differences at the neuromuscular level. Specifically, older adults did not modulate muscle firing patterns relative to limb movements to accommodate increasing movement frequency, whereas younger adults changed the timing of their muscle bursts to meet the required movement speed. These results suggest that older adults have difficulty in flexibly modifying their neural output to peripheral muscles in order to produce changes in movement frequency. Alternatively, older adults may have opted to swing their leg like a pendulum at high movement frequencies to utilize momentum rather than actively controlling the timing of muscle bursts. Thus, the EMG patterns observed in young and older adults may have been a reflection of a difference in strategy between two groups. It is interesting to speculate that the strategy adopted by older adults may have been in response to perceived difficulties in coordinating arm and leg movements with a metronome.

An unexpected finding was that despite longer overall reaction times in older adults to secondary task probe stimuli compared to younger adults, age differences in RT were constant across variations in limb combinations and movement direction. These results

suggest that the age-related differences in probe RT may reflect increased mental effort exerted by older adults to successfully perform the interlimb coordination tasks, rather than a decreased attentional capacity in the aged. Alternatively, it is possible that neural cross-talk between the vocal RT task and the interlimb coordination task may have contributed to the increase in RT from single- to dual-task performance. Given that there is some evidence of a reduction in inhibitory control with aging (e.g., McDowd & Shaw, 2000), it was hypothesized might be expected that older participants would experience greater cross-talk between the two tasks than younger adults. Thus it was first necessary to further investigate attentional function during interlimb coordination using a technique that would allow the evaluation of attentional effort without the influence of structural interference.

The aim of the second study was to investigate the electrophysiological correlates of age-related changes in central cost during an interlimb coordination task using a dual-task paradigm. The P300 of the ERP was chosen as it is argued to provide a pure measure of attentional resource allocation independent of motor preparation and execution. As the aim was to compare the attentional cost required to achieve similar primary task performance between younger and older adults, participants were allowed to self-determine coordination task movement speeds. Although older adults revealed slower reaction times to target

stimuli in the secondary visual oddball task compared with younger adults, amplitude and latency of the P3b did not show age-related differences. These findings are consistent with previous research examining age differences in reaction time tasks (Falkenstein et al., 2006; Yordanova et al., 2004) suggesting that age-related motor slowing may originate at stages later than those indexed by P3b amplitude. For example, Falkenstein and colleagues (2006) observed substantial age differences in the response generation processes in the motor cortex contralateral to the responding hand. The differences between younger and older adults were reflected by larger and more extended motor related potential (MRPs), suggesting that extensive and longer activation of the motor cortex is required in older adults for the generation of a motor response. Thus, the lack of age-related differences in overall P3B amplitude in the second experimental study is consistent with view that age-related changes in motor task performance originate in a motor generation process that is mainly organised in the motor cortex, rather than stimulus processing and motor preparation stages.

There was, however, some evidence in the second experimental study for the operation of a compensation mechanism in the aged brain. As expected, younger adults showed a centro-parietal maxima for P3b. Older adults, in contrast, showed a consistent

level of P3b amplitude across the three midline sites (Frontal, Central, Parietal) suggesting that they involved more brain areas to achieve a performance level similar to that of younger adults. In particular an increased P3b amplitude in frontal sites was consistent with previous ERP studies (Anderer et al., 1996; Friedman et al., 1997; Iragui et al., 1993; Kok, 2000; Pfefferbaum et al., 1980; Pfefferbaum, 1984; Vesco et al., 1993) and may indicate increased cognitive monitoring of performance with aging (Alain et al., 2004; Heuninckx et al., 2005; Heuninckx et al., 2008). Although the operation of compensatory mechanisms may have allowed older adults to successfully perform the motor task, the origin of the age-related deficit in interlimb coordination was still not clear since the index of attentional resource allocation, P3b amplitude, did not differ between younger and older adults. The recent evidence (Falkenstein et al., 2006; Yordanova et al., 2004) of age differences in the stage of motor generation rather than in the central information processing suggested the need for a more direct examination of motor cortex function during the performance of interlimb coordination.

The final part of the research investigated the neurophysiological correlates of interlimb coordination by examining cortical inhibitory processes in older adults. It has been suggested that the additional cortical activations which have been observed in fMRI

studies in older adults may reflect a breakdown in inhibitory processes associated with increasing age (Milham et al., 2002; Nielson et al., 2002). Furthermore, other studies have suggested that intracortical inhibitory processes are important in the coordination of movements involving a hand and foot (Byblow et al., 2007; Sohn et al., 2005; Tazoe et al., 2007).

The final study used transcranial magnetic stimulation to investigate the neurophysiological correlates of age-related changes in the coordination of hand and foot movements. Unlike the previous two experiments, the third experiment used a fixed movement frequency (1.0 Hz) for both groups. Older adults demonstrated less coordination stability than younger adults, particularly when performing non-isodirectional movements with ipsilateral limbs (Hiraga et al., 2004, 2005; Meesen et al., 2006). Age-related decline in interlimb coordination performance may be associated with lack of modulation in cortical inhibitory function. Inhibition in younger adults was elevated during the ipsilateral limb combinations, particularly in the most difficult non-isodirectional pattern, whereas older adults showed a consistent level of cortical inhibition across limb combinations and coordination directions. This result suggested that in older individuals, the decreased ability to modulate cortical inhibitory function may lead to degraded performance in tasks

requiring the coordination of upper- and lower-limbs.

8.2 General Discussion

Overall findings from the empirical studies in the current research indicate that at both muscular and neural levels, functional flexibility in the human motor system degrades with advancing age. Older adults seemed to have difficulty in modulating their neuromuscular function (Part 1) and cortical inhibitory function (Part 3) as well as showing a shift in cortical brain activation patterns during information processing (Part 2). The lack of modulation of muscle firing patterns in older adults in response to increased movement speed may be related to reported age-related changes in muscle activation patterns when coordinating groups of muscles. Previous research has suggested that older adults co-activate agonist and antagonist muscles more frequently than younger adults in order to control postural balance and that this may be beneficial in overcoming postural perturbations by stabilizing joint position (see review, Woollacott, 2000). In addition to the co-activation of agonist and antagonist muscles, older adults have difficulty in regulating rapid muscle activations (see review, Barry & Carson, 2004). For example, in a study by Christou and Carlton (2001), participants performed rapid discrete isometric contractions,

matching their force level with a given trajectory which were displayed on the computer screen. Older adults showed greater variability in force production compared to younger adults. The authors concluded that the increased variability was due to a declined ability in the temporal characteristics of force production with advancing age. Thus, the lack of modulation of muscle activation between upper- and lower-limb muscles found in Experiment 1 of the present research may be a reflection of a decline in the temporal control of muscle firing patterns in older adults. Support for this suggestion was the finding that age related performance differences were particularly evident at high movement speeds, consistent with previous research demonstrating reduced performance associated with increased movement speed (e.g., Greene & Williams, 1996; Heuninckx et al., 2004).

As previous research has shown, the second study found higher cortical activity in the frontal areas of older adults compared to younger adults during the performance of interlimb coordination. Moreover, the pattern of brain activation observed in older adults seemed to be beneficial in stabilising interlimb coordination since older adults showed similar levels of coordination performance to young adults. This pattern of activation may be evidence of a compensatory mechanism associated with advancing age as discussed in Chapter 5 (Heuninckx et al., 2005; Heuninckx et al., 2008; Mattay et al., 2002; Ward &

Frackowiak, 2003; Wu & Hallett, 2005).

Previous research has identified that an impaired ability in the allocation of attentional resources as a mechanism responsible for age related decline in motor function (Kramer et al., 1999; Serrien et al., 2000). Rather, the lack of modulation in cortical inhibitory function across various conditions in older adults in the third empirical study suggests that declined control of cortical inhibition in M1 may be a more important contributor to age-related changes in the performance of interlimb coordination.

The results of the third study suggest that cortical inhibitory control plays a role in the performance of interlimb coordination with increased level of inhibition being exhibited during the non-isodirectional ipsilateral limb coordination in young adults. This result is consistent with the view that maintaining non-isodirectional coordination patterns requires resisting a phase transition to more stable isodirectional pattern (Greene & Williams, 1996; Swinnen, Young, Walter, & Serrien, 1991). In addition to interactions within the motor cortex, secondary motor areas may contribute to the directional organisation of interlimb coordination. Recently, Byblow et al. (2007), using a paired-pulse TMS protocol, suggested that dorsal premotor cortex (PMd) was possibly involved in the regulation of directional coupling between upper- and lower-limbs. An involvement of PMd in directional control of

hand and foot coordination is also consistent with a previous fMRI study by Heuninckx and colleagues (Heuninckx et al., 2005). In addition, Carroll, Baldwin, Collins, and Zehr (2006) suggested that rhythmic arm movements are mainly controlled in subcortical regions after finding reduced M1 excitability during cyclic arm movement when compared with tonic contraction. Thus these results indicate that PMd and subcortical regions are also involved in the regulations of interlimb coordination. Furthermore, the third study found overall higher intracortical inhibition in younger adults during ipsilateral limb combination compared to contralateral limb combination. A possible explanation offered for this increase in inhibition during ipsilateral limb combination was the involvement of an anticipatory postural adjustments (APAs) mechanism that may induce changes in the balance between excitatory and inhibitory processes, both within and between cortices. The APA mechanism operates to stabilize posture in order to counterbalance the initial movement of other parts of body (Baldissera & Esposti, 2005). For example, if the interlimb coordination task involves right hand and foot, APAs operate to attenuate possible displacement of the centre of mass (CoM) by, in this case, preparing to activate muscle groups in the left side of the body. At the cortical level, APAs may induce decline of cortical inhibition in the right hemisphere to allow left side of the body to prepare a

necessary movement that counterbalances the movement of the right hand side of the body. That is, the APAs mechanism leads the right hemisphere to prepare for the necessary action to compensate for the body movement resulting from the movement of the right hand side of the body. Lee and colleagues (Lee, Gunraj, & Chen, 2007) found that intracortical inhibition (ICI) induced by TMS reduced interhemispheric inhibition (IHI), suggesting that elevated intracortical inhibition in one hemisphere may result in reduced intracortical inhibition in the other hemisphere. Therefore, the elevation of intracortical inhibition found in the third empirical study in Part 3 during the coordination of ipsilateral limbs may have been beneficial to reduce IHI which may have consequently increased cortical excitability in the right hemisphere. In fact, Sohn and colleagues (2003) found reduced intracortical inhibition during the voluntary movement of the ipsilateral hand supporting the notion that an APAs mechanism might be responsible. The decreased IHI may allow the contralateral side of the body to prepare a necessary movement that compensates for the disturbance produced by the movement of ipsilateral upper- and lower-limbs. In contrast, the coordination performance by contralateral limbs may require less postural adjustment. Nevertheless, these explanations are highly speculative as no previous study has directly investigated cortical activity during interlimb coordination comparing ipsilateral and

contralateral limb combination with isodirectional and non-isodirectional coordination modes.

8.3 Future Research Directions

The present results suggest that degraded performance of interlimb coordination in older adults may be linked to a lack of modulation of cortical inhibitory function. It has also been suggested that degraded sensory information processing in older adults may underlie age-related differences in interlimb coordination. It would be of interest in future research to investigate a possible link between deficits in the processing of sensory information and the ability to modulate inhibitory function. Recently Bock and colleagues (Bock, Pipereit, & Mierau, 2007) manipulated proprioceptive information from the limbs non-invasively and temporarily by applying vibration to the forearm flexors and extensors. Following vibration participants showed reduced performance in force production and haptic shape perception tasks. Of interest would be to examine corticospinal inhibitory functions prior to, during, and following a period of vibration.

A second avenue for future research would be to use repetitive transcranial magnetic stimulation (rTMS) to transiently disrupt neural activity in a specific areas of the brain

(e.g., M1, PMd, SMA) by creating a virtual lesion (Walsh & Rushworth, 1999). Application of rTMS to the brain areas which have been found to be important parts of the motor network involved in interlimb coordination (e.g., Debaere et al., 2001) may show differential effects in young and older adults.

8.4 Conclusion

In Experiment 1 an age difference was evident particularly in the most demanding condition in which participants were required to divide their attention during coordination of ipsilateral limbs at maximum speed. Experiment 2 demonstrated that when coordination performance between younger and older adults was similar, older adults showed greater activity in frontal brain areas during the performance of coordination tasks than younger adults. The results of the final study suggest that declined ability to modulate corticospinal activity in M1 with age may be associated with age-related changes in the performance of interlimb coordination.

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Appendices

Appendix A: Adopted Mini-Mental State Examination

NAME _____ DATE _____

ORIENTATION

Score one point for correct answers to each of the following questions:

What is the date?
day?
month?
Year?
season? 5 points ( )

What is the name of this
Building
floor
suburb
State ?
Name of mountain? 5 points ( )

REGISTRATION

May I test your memory? (name 3 unrelated objects-**Apple, bed, stapler**, or **orange, tree, suitcase**-clearly, slowly, one per second. When you have said all 3, ask the participant to repeat them. The first repetition determines the score, 0-3, but keep saying them until all 3 can be repeated, up to 6 trials.) After recall say- **Remember these words as I'll ask you to recall them again later.**

3 points ( )

ATTENTION AND CALCULATION

Can you subtract 7 from 100, and then subtract 7 from the answer you get and keep subtracting 7 until I tell you to stop? (*Stop after 5 subtractions, score the total number of correct answers*).

93 86 79 72 65 5 points ( )

RECALL

Can you recall the 3 words I asked you to remember?

3 points ( )

LANGUAGE

Point to and ask the participants to name – score 1 points for each.

A pencil A watch 2 points ( )

Can you repeat this sentence for me? (*one trial only, score 0-1*)
"No ifs, ands or
buts". 1 point ( )

Give the participants a blank piece of paper and have them doing the following. Score 1 point for each part correctly executed.

Take the paper in your right hand
Fold the paper in half
Put the paper on the floor 3 point ( )

Can you write me a sentence, please? *(to score 1 points it must contain a subject, a verb and make sense)*

1 point ( )

Here is a drawing (See following page). Please copy the drawing on the same paper. *(to score 1 point all 10 angles must be present and 2 must intersect-the juncture forms a four sided figure)*

1 point ( )

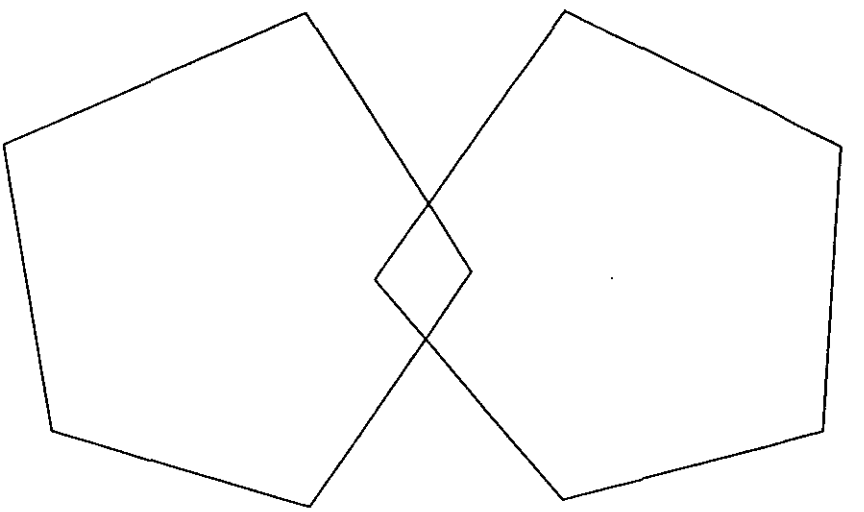
TOTAL SCORE (=30) ( )

From Dick et al. (1984) J. Neurol. Neurosurg. Psychiatr. 47. 496-9.
The authors suggested that a score of 23 or less is "Suggestive of cognitive impairment". However, this is based on WAIS IQ scores and is therefore likely to be fairly insensitive. The "Mini Mental" is also insensitive to right hemisphere damage.

Dick, J. P. R., Guiloff, R. J., Stewart, A., Blackstock, J., Bielawska, C., Paul, E. A., & Marsden, C. D. (1984). Mini-mental state examination in neurological patients. Journal of Neurology, Neurosurgery, and Psychiatry, 47, 496-499.
http://jnnp.bmjjournals.com/cgi/content/abstract/47/5/496

NAME_____ DATE

Drawing



Appendix B: Screening Questionnaire for the Experiment 2 (ERPs study)

Date...../...../..... Participant Code..... Age..... yrs..... mths Sex: M / F

Neural correlates of performance trade-offs and Interference in dual task performance.

Medical History
Are you currently suffering from anxiety or depression?.....

Do you have a heart condition or any other serious physical condition?

.....

Are you currently taking any prescription medication? If so, what medication?

.....

Have in the past taken any medications for psychological condition(s)? If so, what medications?

.....

Have you ever had or are you now suffering from any of the following (please circle):

Fits or convulsions	Yes	No
Epilepsy	Yes	No
Giddiness	Yes	No
Concussion	Yes	No
Severe Head Injury	Yes	No
Loss of Consciousness	Yes	No

Handedness
For each of the activities below, please tell us:
Which hand do you prefer for that activity?
Do you *ever* use the other hand for the activity?

Preferred hand? Ever use other hand?				
Writing	L	R	Y	N
Drawing	L	R	Y	N
Throwing	L	R	Y	N
Using scissors	L	R	Y	N
Using a toothbrush	L	R	Y	N
Using a knife (without fork)	L	R	Y	N
Using a spoon	L	R	Y	N
Using a broom (upper hand)	L	R	Y	N
Striking a match	L	R	Y	N
Opening a box (lid)	L	R	Y	N

Do you ever confuse left and right?.....

How many people in your immediate family are left handed?.....

Drinking and Smoking History (please circle 1 answer)
On how many days last week did you drink alcohol?

None
One or two days
Three or four days
Five or six days

Every day

Do you usually drink?

Never
During weekdays
Friday night
Weekends

How many drinks would you usually have at one time?

One or two
Three to five
Five to eight
Eight to twelve
More than twelve

Do you get drunk?

Never
Rarely
Once a month
Once a week
More frequently

How often do you smoke a cigarette?

Never
Less than 5 per week
Less than 5 per day
5 to 9 per day
10 to 19 per day
20 to 39 per day
Over 40 per day

Do you or have you in the past used marijuana? (please circle) Yes No

a) Have you used marijuana in the last two weeks? Yes No

b) Have you used any other form of illicit drug in the last 6 months?
Yes No

Vision
Do you have any difficulties with vision? (please specify)

.....

If yes, are these difficulties corrected (i.e. glasses/contacts)

.....

Note: It is a formal requirement of the Human Research Ethics Committee (Tasmania) Network that the information provided on this questionnaire will be held under security to comply with confidentiality regulations and to protect your privacy. You can be assured that information will be available only to the principal researcher and not to any other party. The questionnaire will be destroyed following completion of the project.

Thank you for your Participation!

Appendix C: Screening Questionnaire for the Experiment 3 (TMS study)

Date...../...../..... Participant Code..... Age..... yrs..... mths Sex: M / F
Inhibitory control of inter-limb limb coordination

Medical History
Are you currently suffering from anxiety or depression?.....

Do you have a heart condition or any other serious physical condition?

.....

Are you currently taking any prescription medication? If so, what medication?

.....

Have in the past taken any medications for psychological condition(s)? If so, what medications?

.....

Have you ever had or are you now suffering from any of the following (please circle):

Stroke	Yes	No
High Blood Pressure > 140 / 90	Yes	No
Diabetes	Yes	No
Arthritis	Yes	No
Fits or convulsions	Yes	No
Epilepsy	Yes	No
Giddiness	Yes	No
Concussion	Yes	No
Severe Head Injury	Yes	No
Loss of Consciousness	Yes	No

Handedness
For each of the activities below, please tell us:
Which hand do you prefer for that activity?
Do you *ever* use the other hand for the activity?

Preferred hand? Ever use other hand?				
Writing	L	R	Y	N
Drawing	L	R	Y	N
Throwing	L	R	Y	N
Using scissors	L	R	Y	N
Using a toothbrush	L	R	Y	N
Using a knife (without fork)	L	R	Y	N
Using a spoon	L	R	Y	N
Using a broom (upper hand)	L	R	Y	N
Striking a match	L	R	Y	N
Opening a box (lid)	L	R	Y	N

Do you ever confuse left and right?.....

How many people in your immediate family are left handed?.....

Drinking and Smoking History (please circle 1 answer)

On how many days last week did you drink alcohol?	None One or two days Three or four days Five or six days Every day
Do you usually drink?	Never During weekdays Friday night Weekends
How many drinks would you usually have at one time?	One or two Three to five Five to eight Eight to twelve More than twelve
Do you get drunk?	Never Rarely Once a month Once a week More frequently
How often do you smoke a cigarette?	Never Less than 5 per week Less than 5 per day 5 to 9 per day 10 to 19 per day 20 to 39 per day Over 40 per day

Do you or have you in the past used marijuana? (please circle)	Yes	No
a) Have you used marijuana in the last two weeks?	Yes	No
b) Have you used any other form of illicit drug in the last 6 months?	Yes	No

Vision

Do you have any difficulties with vision? (please specify)

.....

If yes, are these difficulties corrected (i.e., glasses/contacts)

.....

Note: It is a formal requirement of the Human Research Ethics Committee (Tasmania) Network that the information provided on this questionnaire will be held under security to comply with confidentiality regulations and to protect your privacy. You can be assured that information will be available only to the principal researcher and not to any other party. The questionnaire will be destroyed following completion of the project.

Thank you for your participation!